UNIVERSITY OF CAMBRIDGE
Faculty of Economics

CAMBRIDGE WORKING PAPERS IN ECONOMICS

An overview of the electrification of residential and commercial heating and cooling and prospects for decarbonisation

Mathilde Fajardy

David M Reiner

Abstract

Heating and cooling are responsible for over 50% of the world's final energy consumption, and over 40% of global CO2 emissions. With an increasingly decarbonised electricity grid, the electrification of heating offers one potential alternative to the incumbent, heavily fossil-fuel dominated heating system. However, the high penetration of renewables, the high seasonality and hourly variability of heat demand, and an increasing domestic demand for energy services, including cooling, pose significant balancing challenges for both hourly system operation and the long-term investment decision planning of electricity systems. The combination of both demand-response measures and the integration of flexible systems will be required to deliver low carbon heating and cooling, while integrating an increasing share of renewable electricity, and managing peak load. We provide a global overview of the technical, economic and policy challenges and opportunities to decarbonise heating demand through electrification, in the context of rising demand for cooling services.

Reference Details

CWPE	20120
Published	9 December 2020
Key Words	Heating, cooling, electrification, decarbonisation, peak load management, demand response
JEL Codes	L95, O13, Q41, Q42
Website	www.econ.cam.ac.uk/cwpe

An overview of the electrification of residential and commercial heating and cooling and prospects for decarbonisation

EPRG Working Paper 2037

Cambridge Working Paper in Economics 20120

Mathilde Fajardy and David M Reiner

Abstract

Heating and cooling are responsible for over 50% of the world's final energy consumption, and over 40% of global CO2 emissions. With an increasingly decarbonised electricity grid, the electrification of heating offers one potential alternative to the incumbent, heavily fossil-fuel dominated heating system. However, the high penetration of renewables, the high seasonality and hourly variability of heat demand, and an increasing domestic demand for energy services, including cooling, pose significant balancing challenges for both hourly system operation and the long-term investment decision planning of electricity systems. The combination of both demand-response measures and the integration of flexible systems will be required to deliver low carbon heating and cooling, while integrating an increasing share of renewable electricity, and managing peak load. We provide a global overview of the technical, economic and policy challenges and opportunities to decarbonise heating demand through electrification, in the context of rising demand for cooling services.

Keywords	heating, cooling, electrification, decarbonisation, peak load management, demand response
JEL Classification	L95, O13, Q41, Q42

Contact	m.fajardy@jbs.cam.ac.uk
Publication	December 2020
Financial Support	EPSRC Grant EP/P026214/1

An overview of the electrification of residential and commercial heating and cooling and prospects for decarbonisation[1]

Mathilde Fajardy and David M. Reiner

EPRG, Judge Business School, University of Cambridge

Abstract

Heating and cooling are responsible for over 50% of the world's final energy consumption, and over 40% of global CO2 emissions. With an increasingly decarbonised electricity grid, the electrification of heating offers one potential alternative to the incumbent, heavily fossil-fuel dominated heating system. However, the high penetration of renewables, the high seasonality and hourly variability of heat demand, and an increasing domestic demand for energy services, including cooling, pose significant balancing challenges for both hourly system operation and the long-term investment decision planning of electricity systems. The combination of both demand-response measures and the integration of flexible systems will be required to deliver low carbon heating and cooling, while integrating an increasing share of renewable electricity, and managing peak load. We provide a global overview of the technical, economic and policy challenges and opportunities to decarbonise heating demand through electrification, in the context of rising demand for cooling services.

1. Introduction

Heating and cooling involve multiple applications across various sectors and usually refer to temperature management of space, water and processes, in residential and commercial buildings and across industry. The diversity of applications makes accounting for cooling – and especially heating-related energy demand and emissions across various sectors challenging. Even extracting consistent data on heat-related energy demand and emissions can be very laborious, since national statistics will often aggregate at the sector (for example buildings, industry) or sub-sector (residential, commercial, given industry) level, or simply lump together heat and electricity.

By any accounting, numbers for global heating and cooling energy demand and associated CO_2 emissions are staggering. In 2017, total heating demand accounted for 58800 TWh of energy demand (half of total energy demand) and 12.6 $GtCO_2$ of emissions (IEA 2018a; IEA Statistics 2019). So far, demand for cooling is only responsible for 1900 TWh (1.7 per cent of total energy demand) and 1.1

[1] A version of this paper will appear as a chapter in the *Handbook on the Economics of Electricity Markets*, edited by Jean-Michel Glachant, Paul L. Joskow and Michael G. Pollitt to be published by Edward Elgar in 2021. We are grateful for helpful comments from the editors. We acknowledge support from EPSRC Grant EP/

$GtCO_2$ (3.4 per cent of global emissions), but has increased by 150 per cent in less than 20 years (IEA 2019a and 2019b). Unless otherwise noted we will use 2017 values throughout.

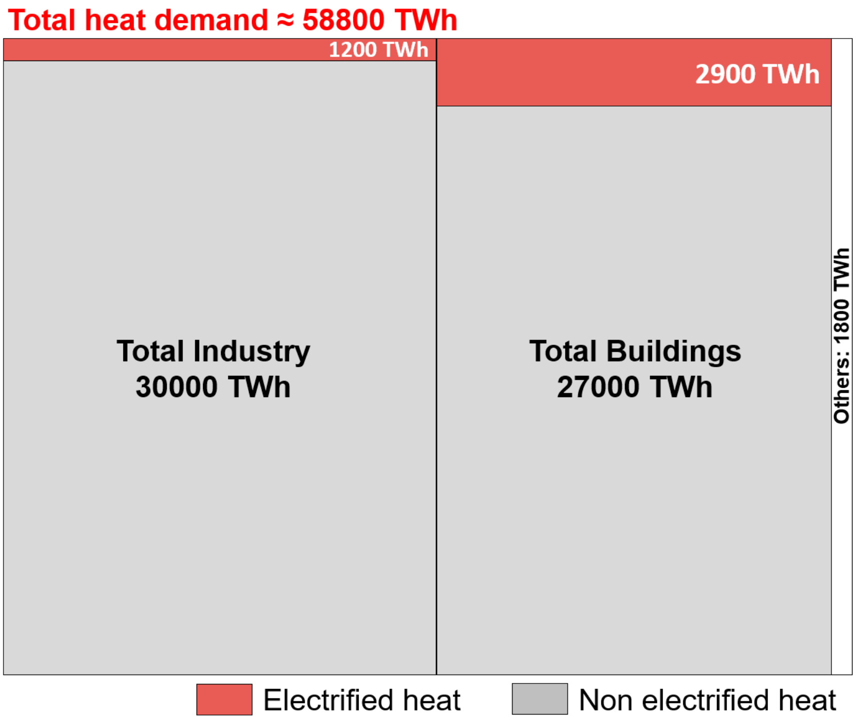

Figure 1 Total and electrified heat demand per sector. Sources: IEA (2018a), (2019a), (2019b)**.**

Process, space and water heating is still largely dominated by direct combustion of fossil fuels (apart from traditional biomass, which is considered neutral from a carbon accounting perspective). This can be explained by the high energy density of these fuels and their ability to meet a variable heat demand. Thus, only 7 per cent of total heat demand is electrified (IEA 2018a), mostly in buildings, and less than 6 per cent is supplied by district heating, whereas 85 per cent is via direct combustion of fossil fuels (IEA Statistics 2019). Although 7 per cent is the global average, electrification rates vary greatly across the world, depending on availability and cost of electricity or its competitors. Figure

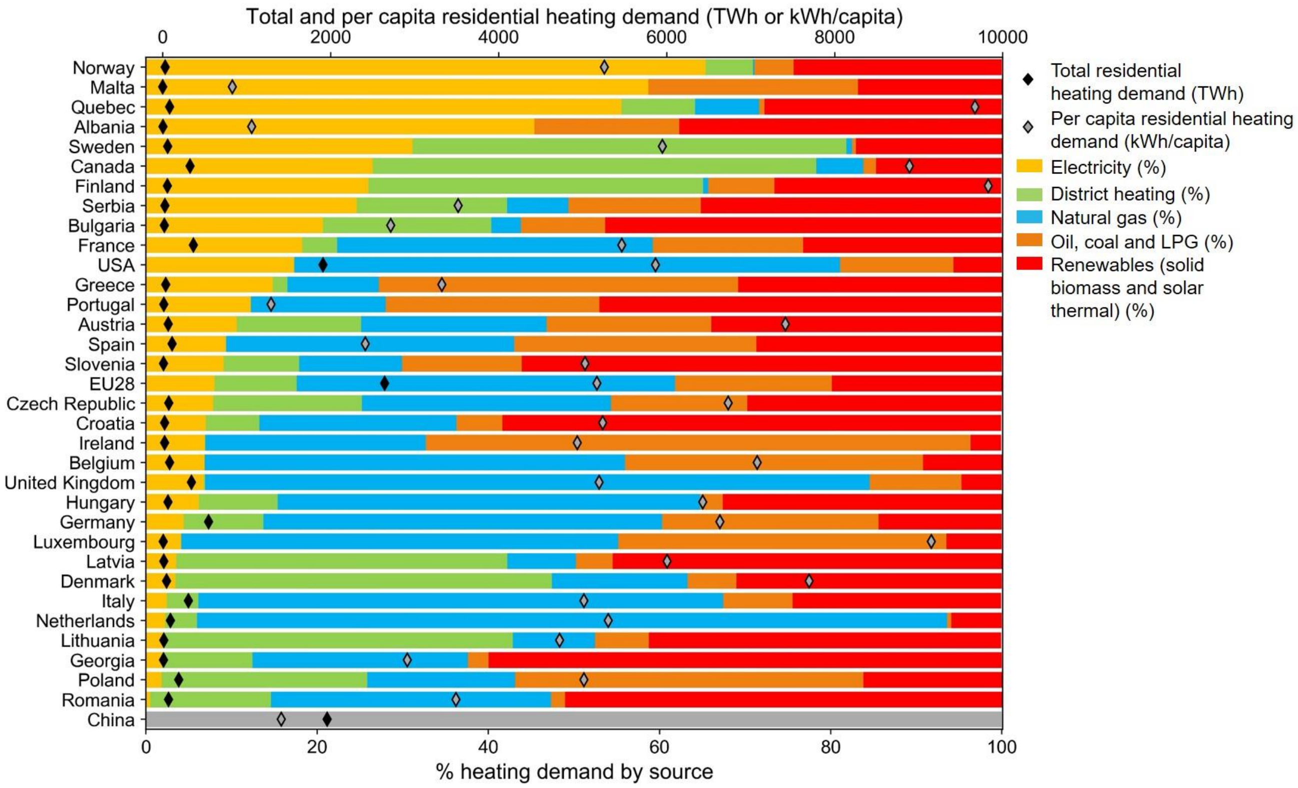

Figure 2 provides total and per capita residential heating demand by source in selected regions. For example, UK residential heating is 85 per cent reliant on natural gas encouraged by gas reserves in the North Sea. In Sweden, however, solid biomass boilers meet 17 per cent of residential heating demand, and district heating make up 51 per cent of heating demand, of which 87 per cent is sourced from biofuels and wastes (IEA 2019c), owing to the high availability of bio-feedstock and established bioenergy supply chains. In regions which boast high availability of low-cost electricity, often based on hydroelectric power, such as Norway or Quebec, electrification of residential heat reaches 56-65 per cent (European Commission 2019b; Natural Resources Canada 2019). Otherwise, high penetration rates are only found in countries with low heat demand, such as Albania or Malta, which highlights the difficulty of electrifying heat, since variability of heat demand poses significant load balancing challenges (European Commission, 2019b).

While most climate policies have focused on decarbonising the power sector, the heat sector has remained virtually untouched. In 2017, only 10 per cent of heat was generated from renewable sources (IEA 2018a). The largest share of renewable heat comes from bioenergy, mainly for industrial applications, followed by renewable electricity, mainly in buildings. Only 1100 TWh comes from renewable electricity (IEA 2018a).

Electrification of heating enables the move from a highly dispersed CO_2 emissions model, to a model where CO_2 emissions are centralised around electricity production, and hence easier to abate. As current heating needs are largely met by fossil fuels and traditional biomass, it also means that supply is still subject to the availability and cost of these resources. In 2018, the USA, Russia and the Middle East were responsible for over 60 per cent of global natural gas production (IEA Statistics 2019). From an energy security perspective, electrification enables diversification, by decoupling heat sinks from heat sources. The integration of renewables, modern biomass and/or abated fossil-fuel electricity (for example, using carbon capture and storage or CCS) could provide more flexibility and make the overall energy system more resilient than the incumbent one.

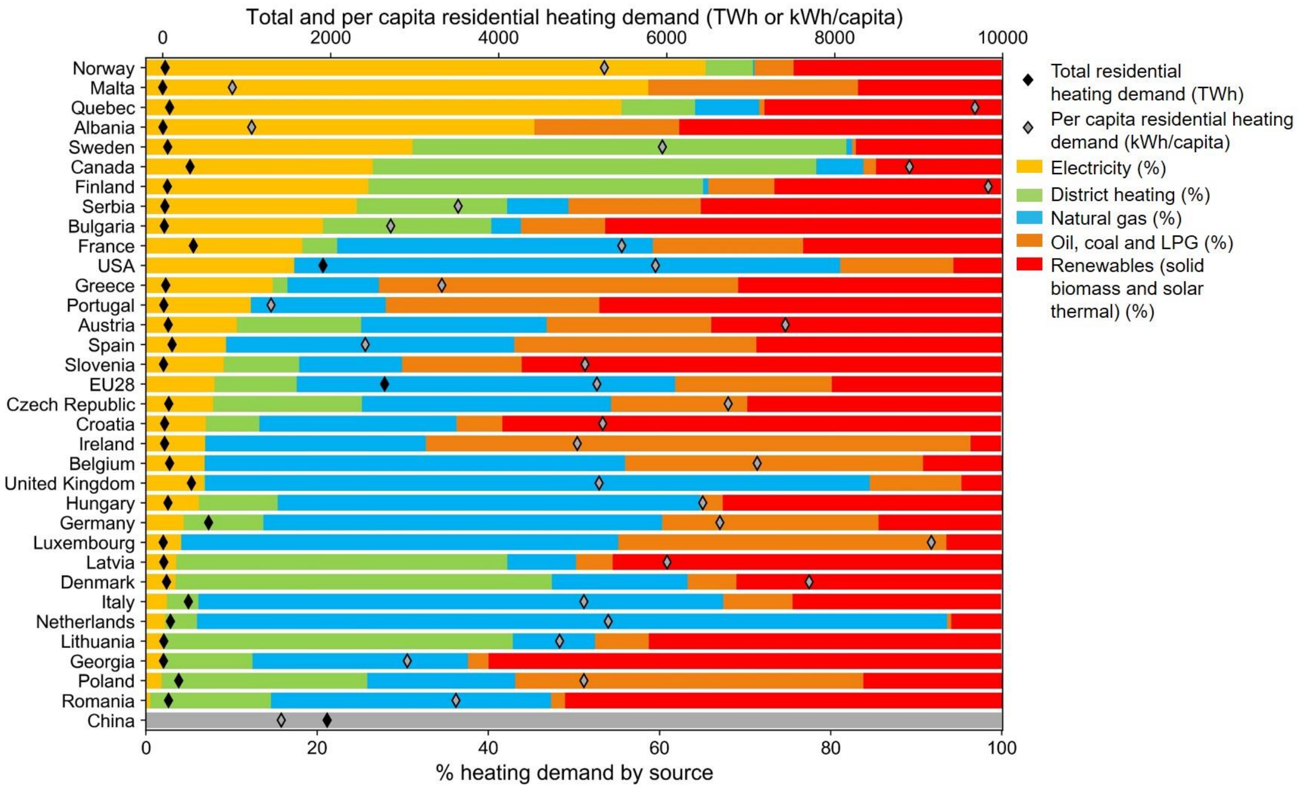

Figure 2 Total and per capita residential heating by source in a selection of countries and provinces. Source: authors based on BERC (2018); EIA (2019); European Commission (2019b); Natural Resources Canada (2019*).*

Pathways to electrify heat in the residential and commercial sectors have been explored at the global (IEA 2019a, Knobloch et al. 2019), European (Connolly et al. 2014, Heinen et al. 2018) and national level, in particular in the US (Paige et al. 2017; White and Rhodes 2019), and the UK (Cooper et al. 2016, Element Energy and E4Tech 2018, Strbac et al. 2018, Zhang et al. 2018).

The Paris Agreement’s commitment to limit global temperature increase to ‘well below 2°C’ has been translated into regional, national and sub-national initiatives to reach net zero greenhouse gas emissions by 2050 or earlier at the city (New York), state (California) and country (UK, France, Sweden, Finland, Norway and New Zealand) level. These pledges have resulted in a renewed interest in further exploring deep decarbonisation pathways for the heat sector.

The industrial sector is also responsible for a large fraction of heat demand and associated CO_2 emissions. Globally, about 30 000 TWh are used for space and process heating in industrial sites, and only about 10 per cent of this heat supply is renewable (IEA 2018a). As a result, industrial heat was responsible for roughly 10 per cent of global CO_2 emissions (Friedmann et al. 2019). In the European context, a full electrification scenario of the industrial sector would increase total electricity demand in industry by more than a factor of ten, from 125 TWh to 1713 TWh (Lechtenböhmer et al. 2016). The challenges and costs of electrification of heat in industry are, however, much more context- and industry-dependent than in the buildings sector. Addressing the role of electrification in industrial heating requires detailed assessments of the different uses of heat across different industries in a given regional context. Given the scarcity of such surveys, and the high diversity of heat end-uses in industry, relatively few studies have looked at electrification of industrial heat (Lechtenböhmer et al. 2016; Paige et al. 2017; Beyond Zero Emissions 2018; Friedmann et al. 2019; Luh et al. 2019). For the purpose of this study, we chose to focus on the electrification of residential and commercial heating.

This paper gathers evidence from global and country-level studies to explore the potential for electrification of heating in the building sector. The remainder of this report is structured as follows: Section 2 summarises current heat supply and CO_2 emissions, Section 3 presents the different technology options to decarbonise heating, Section 4 provides an overview of the challenges and opportunities of electrification, Section 5 discusses global and regional outlooks for the role of electrification of heat in the future and Section 6 concludes.

As data related to energy demand and CO_2 emissions from heating is not straightforward to obtain or compare across countries, for the sake of consistency, most of the data we present is derived from various International Energy Agency (IEA) publications.

2. Current Energy Demand, Supply and CO_2 Emissions

First, it is helpful to understand how energy demand in buildings is distributed across different end uses, and how this demand has evolved in the recent past. Figure 3 shows the evolution of the energy demand from the buildings sector by energy service, as well as total floor area and building energy intensity over the past two decades. In spite of efficiency improvements to curb energy use in buildings, the 2000-2017 period has seen a 22 per cent increase in building energy demand. A key driver of this trend is the increase in floor area. While appliance efficiency and building envelope improvements have enabled a 28 per cent drop in building energy intensity, global floor area has increased at a faster rate of 65 per cent over this period. This global increase in floor area is mainly driven by China, which has added 30 billion m^2 since 2000, roughly doubling its total to 58 billion m^2 by 2017, equivalent to 25 per cent of global floor area (IEA 2019a).

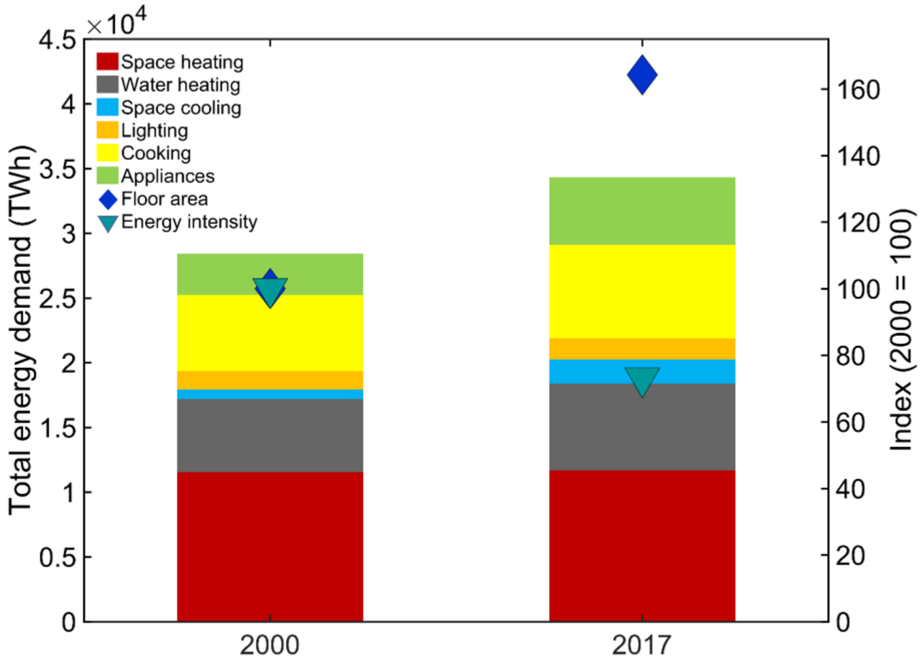

Figure 3 Energy demand in the building sector per end use (y-axis left hand side) and total floor area and energy intensity relative to 2000 (y-axis right hand side), between 2000 and 2017.
Source: authors based on IEA (2019a).

Direct use of coal, oil or natural gas, is responsible for 37 per cent of building energy demand (IEA 2018a), which results in the building sector reaching about 3 $GtCO_2$ in 2017 or 10 per cent of global emissions (IEA 2019a). It can be observed from Figure 4 that these direct emissions have remained constant over the past two decades. When accounting for indirect emissions associated with electricity generation, however, CO_2 emissions have increased from 7.7 $GtCO_2$ in 2000 to 9.5 $GtCO_2$ in 2017, which mirrors the increasing demand trend for new energy services. Accounting for indirect emissions from electricity also explains differences in emissions between the residential and commercial sectors. The commercial sector uses much more electricity (46 per cent, resulting in 43 per cent of indirect emissions), whereas the residential sector uses a significant amount of traditional biomass (30 per cent, that is 8300 TWh), which is considered 'carbon neutral'. While carbon intensity has decreased, it has only declined by 7 per cent between 2000 and 2017 (from 540 kgCO_2/MWh to 490 kgCO_2/MWh) compared to the 59 per cent electricity demand increase in the building sector in the same period.

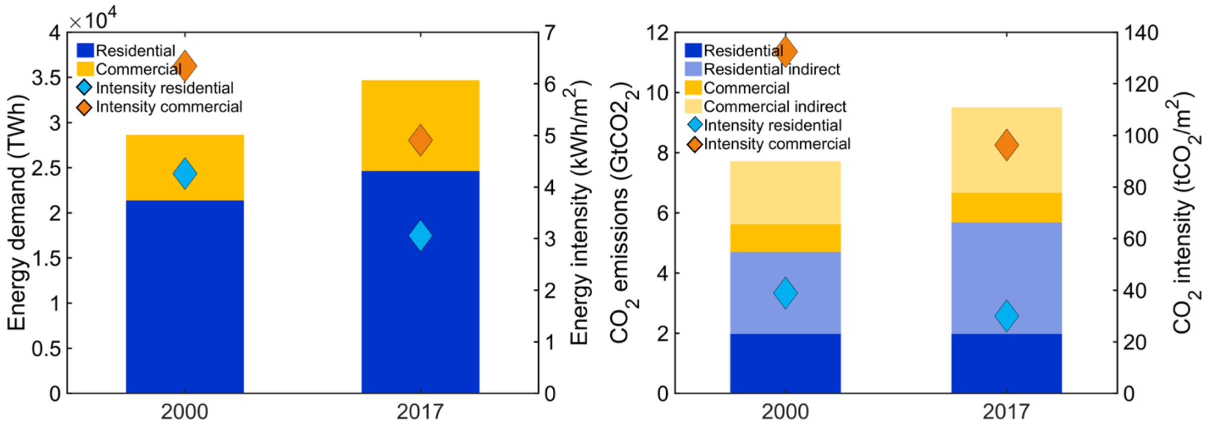

Figure 4 Energy demand and energy intensity (left), and CO_2 emissions and CO_2 intensity (right) of residential and commercial buildings between 2000 and 2017. Note that demand and emissions are displayed as stacked bars and measured on the LHS y-axis whereas the intensities are displayed as diamonds and measured on the RHS y-axis. Source: authors based on IEA (2019a).

2.1 Space and water heating

Globally, space and water heating account for 53 per cent of building energy demand (IEA 2019a). Space heating is the largest contributor to energy demand and accounts for a third of total energy demand. The transition to more efficient technologies (for example, from conventional boilers to condensing boilers) and building efficiency improvements, have kept demand for space and water heating relatively constant, in spite of an increasing building floor area (IEA 2019b). Figure 5 illustrates trends in efficiency improvements in space and water heating in selected regions, between 2000 and 2017. In contrast with the more rapid increase in demand for cooling and electricity services, water heating and space heating only increased by 1 per cent and 18 per cent respectively between 2000 and 2017.

Space and water heating is still overwhelmingly dominated by fossil fuels. Their use is mainly in conventional boilers, while electricity is typically used in conventional resistance heating, which are quite inefficient systems. In 2017, fossil fuel-based and conventional heating equipment accounted for over 80 per cent of heating equipment sales. Excluding traditional use of biomass, water heating is mainly fuelled by fossil fuels and conventional electric boilers (IEA 2019b).

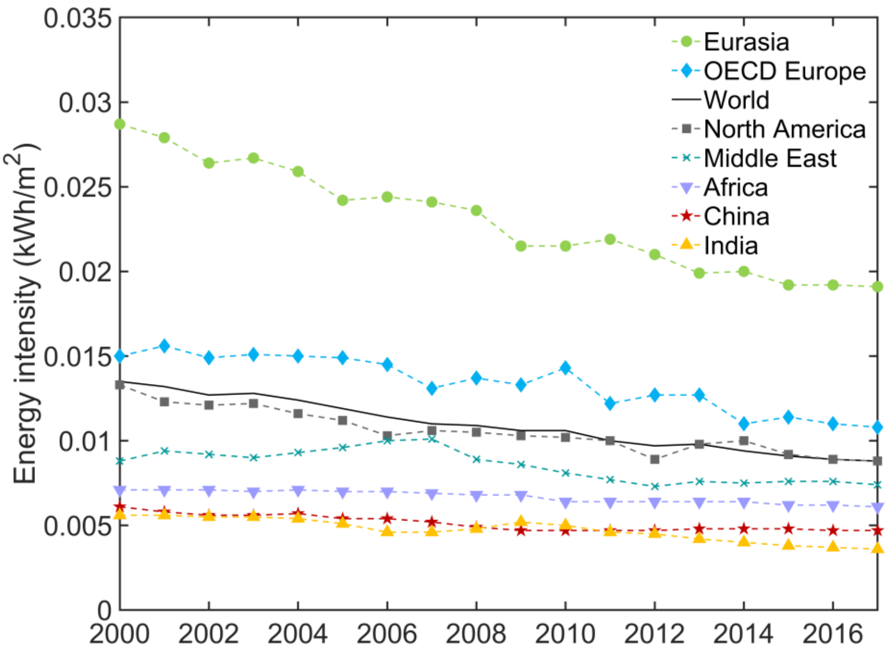

Figure 5 Energy performance improvement of space and water heating between 2000 and 2018. Source: authors based on IEA (2019b)**.**

Geographically, the main contributors to this heating demand are the US, EU, Russia and China (IEA 2019a).

Table **1Error! Reference source not found.** gathers residential heat demand data for China, North America (Canada and the USA), Russia and the EU. Assuming a total global residential water and heat demand of 11 100 TWh (40 EJ) (Gi et al. 2018), these four regions make up 70 per cent of total residential heating demand (see Table 1 for details). Total heating demand per capita, however, varies greatly from one region to another, as a function of building efficiency and level of development. While residential heating demand per capita is over 8800 kWh in Canada and Finland, it falls to 5000 kWh in Poland and the Netherlands, and to 1400 kWh in China (BERC 2018, European Commission 2019b, Natural Resources Canada 2019).

These same regions are also leading the drive for alternatives to fossil-based heating, including solar thermal technologies (China), high efficiency heat pump water heaters (Japan, US, Europe) and hydrogen fuel cells (Japan) (IEA 2019b).

Table 1 Residential space and water heating demand per region in 2017

Region	Demand (TWh)	Note and references
Russia	970	Centralised and decentralised heating demand in Russia from 2009 (Nekrasov et al. , 2012)
China	1960	Urban residential space and water heating demand and northern urban district heat demand from 2016 (BERC 2018)
USA	1910	2017 total residential space and water heating demand (EIA 2019)
Canada	330	2017 total residential space and water heating demand (Natural Resources Canada 2019).
EU	2670	2017 total residential space and water heating demand (European Commission 2019b)

2.2 Space cooling

A second driver of building energy demand is the increasing ownership of appliances and demand for new services (65 per cent increase between 2000 and 2017), especially space cooling (150 per cent increase between 2000 and 2017, see Figure 3) (IEA 2019a. Many drivers can explain these shifts, including population growth (World Bank 2019) and floor area, but also increase in temperatures (IEA 2018b), urbanisation (Mohajerani et al. 2017) and income level (Cayla et al. 2011) [see Box 1]. In 2017, space cooling represented only 6 per cent of energy use in the buildings sector but is currently the fastest increasing component. Ownership of air conditioning (AC) units is highest in Japan (90 per cent) and in the USA (90 per cent) (IEA 2018b). The China AC market has become one of the largest in the world, currently accounting for one third of global AC sales, leading to dramatic increases in AC ownership from 15 per cent of households in 2000 to 60 per cent in 2017. The take-up of AC units has been slower in India, Southeast Asia and Africa but is expected to accelerate in the next decade. Brazil, India, Indonesia and Mexico are rapidly catching up (IEA 2019d). For example, AC ownership in India has doubled from 2 per cent of households in 2010 to 4 per cent in 2016 (IEA 2018b). Penetration rate, of course, does not necessarily imply high consumption since this will depend on the number of rooms air conditioned and usage patterns such as the temperature and the hours used. In Japan, for example, despite having one of the highest penetration rates, space cooling only makes up some 5 per cent of household energy use, compared to Saudi Arabia where air conditioning accounts for over 70 per cent of household electricity use (Enerdata 2019).

Box 1: Increasing demand for cooling and broader energy services

Demand for energy services has risen dramatically since 2000, which can be explained by the following factors:

- Demography: world population grew by 23 per cent between 2000 and 2017, with developing and emerging economies such as Sub-Saharan Africa and South Asia propelling the trend, 58 per cent and 29 per cent respectively (World Bank 2019).
- Climate: increases in air temperature and humidity levels over prolonged periods of time have driven up sales of cooling units around the world. Global air conditioning units sales increased by 16 per cent between 2017 and 2018 alone, after a particularly hot summer where many cities around the world reached record breaking temperatures for an extended period of time (IEA 2018b).
- Income level and development: Research suggests a high correlation between household energy demand and income (Cayla et al. 2011). In Singapore, where the average annual humidity is over 80 per cent, 99 per cent of households are equipped with air conditioning. By comparison, in India, where summer temperatures can reach over 50°C, only 4 per cent of households own an AC (IEA 2018b). As income level increases in emerging economies, appliance ownership and energy consumption ramp up.
- Urbanisation: The world's population is moving away out of rural areas into cities. The proportion of the population living in urban environments has increased from 47 per cent to 55 per cent from 2000 to 2017 (World Bank 2019). Demand for energy services has been observed to be higher in urban areas, especially for cooling. This is partly owing to higher income and urban population living more energy-intensive lifestyles, partly due to higher temperatures in urban environments. This 'heat island effect' is mainly caused by the increasing density of heat absorbing material (for example, asphalt in roads and pavement and dark rooftops) and the reduced amount of natural vegetation (Mohajerani et al. 2017). For AC units which release hot air, the heat island effect generates a vicious circle where cooling demand further drives up cooling demand.

Electricity consumption for space cooling increased twofold globally between 2000 and 2018, over fivefold in India, and eightfold in China (IEA 2018b). The increase between 2017 and 2018 alone is particularly notable – AC sales rose by 16 per cent, which can be explained by record-breaking and prolonged heat waves that hit Europe, Korea, Japan and China in the summers of 2017 and 2018. Since increases in cooling demand have mostly occurred in emerging economies with a high carbon intensity in the power sector, notably China, CO_2 emissions from cooling have tripled since 1990, reaching 1.1 $GtCO_2$ in 2018 and have been rising much more rapidly than cooling demand overall (IEA 2018b). Unlike heating, cooling demand may be better matched with growing reliance on renewables in the power sector, particularly solar PV. In principle at least, the path is more straightforward, but, to date, rapid growth in cooling demand continues to outstrip electricity decarbonisation.

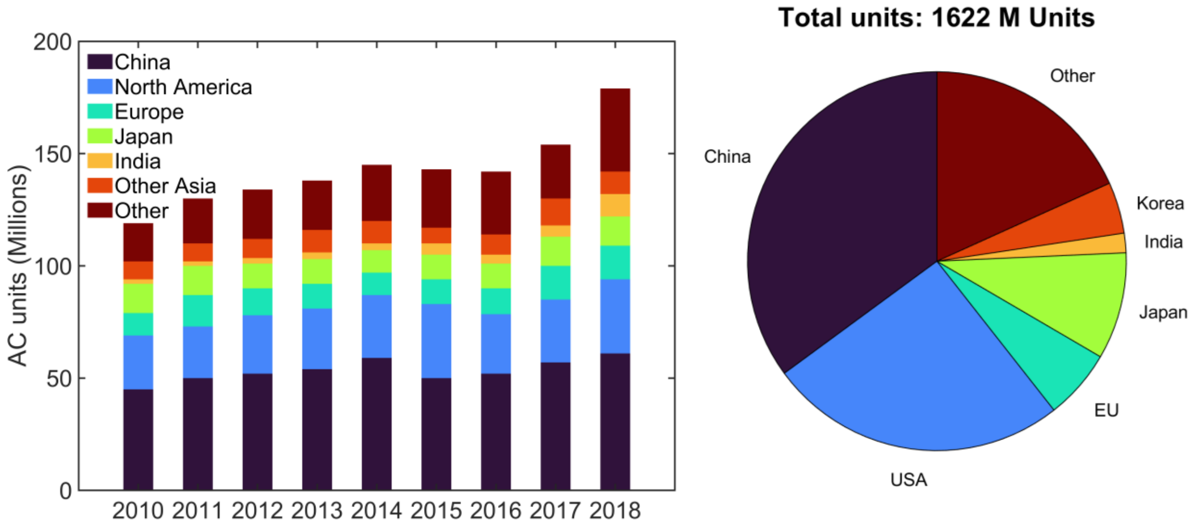

Figure 6 Total AC sales (left) and AC installed capacity in 2016(right).

Source: authors based on IEA (2018b), (2019b).

3. Technology Options to Decarbonise Heating and Cooling Demand in Buildings

While market-ready renewable heating solutions exist, renewable heat only represents 10 per cent of current heat supply (IEA 2018a). Alternatives to the current fossil-fuel-dominated heating system include heat pumps, solar thermal, biomass boilers, district heating and cooling networks, and substituting natural gas with ‘greener gas’, such as hydrogen and biomethane.

Between 2010 and 2017, fossil fuel equipment as a share of total sales dropped slightly from 62 per cent to 59 per cent, as sales of alternatives expanded – conventional electric equipment increased from 20 to 22 per cent, heat pumps increased from 2 per cent to 3 per cent and renewables from 4 per cent to 6 per cent. District heating, on the other hand, has dropped slightly from 11 per cent to 10 per cent of total sales. Heat pump sales increased consistently by around 5 per cent per year over 2010-2017, and by 10 per cent between 2017 and 2018 (IEA 2019b). While this suggests the transition to lower-carbon heating and cooling is underway, a much faster transition is required to meet decarbonisation ambitions.

3.1 Building and District Level Heat Pumps

When exploring electrification of the heating sector, household or district level heat pumps remains the main technology pathway.

Basic Principles

Heat pumps (HP) use a refrigerant (typically R-22 and R-410A in the residential sector) to exchange heat between a heat source – air, water, soil – and a heat sink – air or water. Air-source heat pumps (ASHP) which derive heat from the outside air, and ground-source heat pumps (GSHP), which exchange heat with the soil via underground pipes, are the typical configurations (Staffell et al. 2012). In terms of sinks, air-to-air systems provide space heating by directly warming and circulating the inside air of a property, while air-to-water can provide space heating by circulating hot water around the home via radiators or an underfloor heating system. The hot water can also be stored in a tank for direct use.

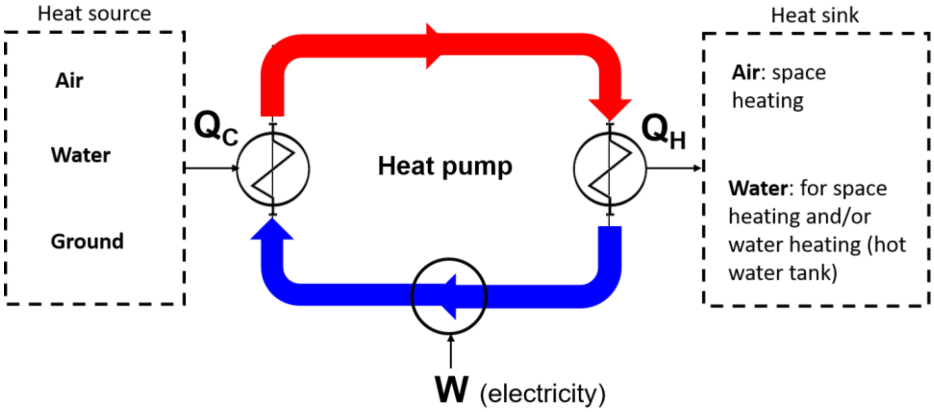

Figure 7 Basic principle of a heat pump. Source: authors.

A heat pump exchanges heat between the cold source and the hot sink by circulating a working fluid in a thermodynamic cycle. The fluid evaporates in a heat exchanger in contact with the outside heat source (air, water or ground), to collect an amount of heat Q_C, It is then brought to a higher pressure in a compressor. This is the part of the process which requires work (W), from electricity. The fluid then condenses in a heat exchanger when in contact with the inside heat sink (air or water), thus delivering heat Q_H to the sink.

The efficiency of a heat pump is measured by its coefficient of performance (COP), which is defined by the amount of heat generated and the amount of work required to compress the fluid. Unlike boilers which are at most 90-95 per cent efficient using advanced technologies (for example condensing boilers), heat pumps typically have an efficiency which is much greater than 100 per cent. This coefficient will be very dependent on the temperature of the heat sink, hence can be variable throughout the year (Staffell et al. 2012). Typically, the COP of HPs is around 3.0, but will drop by 0.6 to 1 for every 10^{o}C difference between indoor and outdoor temperatures (Staffell et al. 2012). Consequently, while COP of four or five can be obtained in milder climates (Mediterranean, Central and Southern China), COP can drop to two in colder climates such as Canada (IEA 2019b). These values are, however, still twice as high as conventional resistive heating.

GSHPs are more resilient to changing outside air temperatures since soils maintain a fairly constant temperature profile throughout the year. However, GSHPs require significant space outdoors as pipes need to be buried underground leading to higher capital costs, while an ASHP is a more compact system, which can be accommodated in a 2 m^2 surface area. Where feasible, geothermal heat pumps can provide a cheaper alternative to ASHPs, due to significantly lower operating costs.

Current sales and outlook

Current heat pump capacity is still very low, having been installed in some 18 million households, which accounts for only 5 per cent of heating equipment sales in 2017 and meeting 3 per cent of global heating needs (IEA 2019b). Like any electrification pathway, decarbonisation of the electricity grid is a pre-requisite if heat pumps are to successfully decarbonise the heating sector. However, because of the much higher efficiency of heat pump systems (300-400 per cent), they could already supply 90 per cent of space heating demand with a lower carbon footprint than condensing gas boilers (IEA 2019a).

Adoption rates of heat pumps are currently higher in moderate climates (US and Western Europe account for 50 per cent of sales) (IEA 2019d). This can be partly explained by the increasing sales of reversible units, which are also used for cooling (EHPA 2019). The highest adoption rates are, however, in the Nordic countries of Sweden, Finland, Norway as well as Estonia, with total heat pump penetration rates between 23 per cent (Estonia) and 42 per cent (Norway) (EHPA 2019, IEA 2019b).

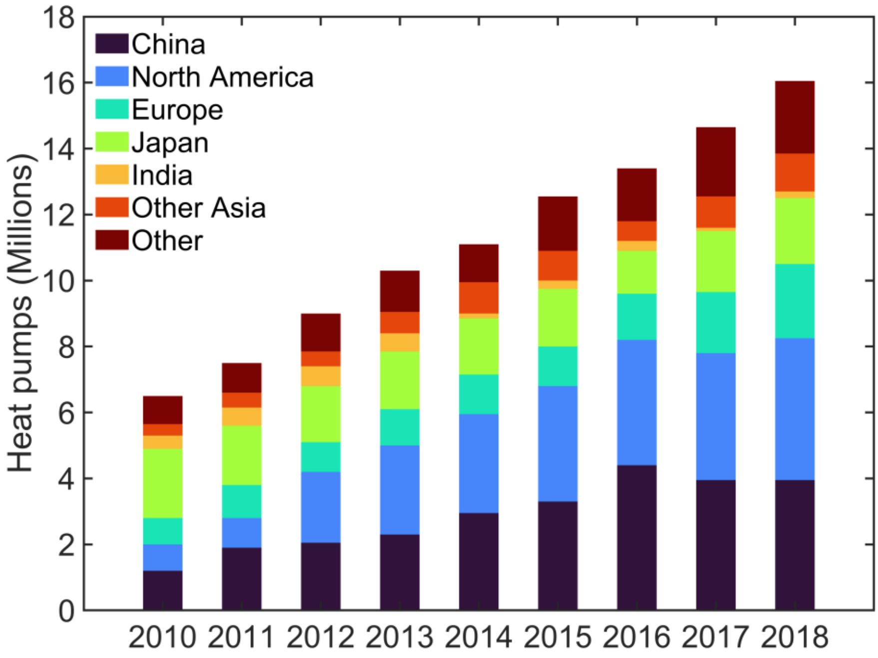

Figure 8 Heat pump sales between 2010 and 2018 in different regions.
Source: authors based on IEA (2019d)**.**

Governmental subsidies can play a large role in technology adoption. Heat pump water heater sales have tripled since 2010, mainly driven by China, which introduced subsidies to replace coal boilers with air-to-water heat pumps (Zhao et al. 2017, Shuxue et al. 2019). Since 2016, growth in heat pump sales has been largely driven by Europe and Japan, due to generous incentives – for example, heat pumps are covered in the UK's renewable electricity portfolio (UK Government 2014) – which have led EU sales to quadruple since 2010.

In pathways going out to 2050, heat pumps become the dominant technology, with approximately one billion households worldwide equipped with a heat pump, operating at a COP of 4.0 on average (IEA 2019a). Reaching this level of deployment would, of course, require significant increases in current levels of uptake.

3.2 Alternative Pathways to Decarbonisation of Heating and Cooling

Aside from electrification, other pathways have been explored to decarbonise heating. These include district heating, solar energy, hydrogen, bioenergy and significant efficiency improvements in gas appliances.

District Heating

District heating typically involves cogeneration plants based on fossil fuel or biomass combustion producing both heat and electricity, but other sources include geothermal, solar nuclear energy or heat pumps. Waste-to-energy (such as in Dublin) also can provide an important source. The heat is then distributed by a network of pipes, which are laid out over a scale ranging from a few homes to an entire city (such as Stockholm or Bucharest). Often district heating can be at the scale of a large commercial facility or an institution with a complex of buildings, such as universities, hospitals or government buildings. By co-producing heat and electricity, these systems can achieve greater efficiencies and lower carbon emissions.

Today, district heating only provides 10 per cent of global heat demand, but constitutes a major source of heating in selected regions (Denmark 44 per cent, Sweden 51 per cent, Russia 42 per cent, China 10 per cent) (European Commission 2019b, IEA 2019a). Future opportunities in this space include fourth generation low-temperature high-efficiency heat networks supplied by large scale heat pumps (Lund *et al.*, 2014; Werner, 2017) but the deployment of these networks is highly dependent on urban configuration, availability and proximity of energy supply and building improvements (IEA 2019b).

To date, 89 per cent of district heat is supplied by fossil energy, resulting in an average carbon intensity of 300 gCO_2/kWh (IEA 2019a). This share is as high as 91 per cent in Russia and 99 per cent in China, where coal supplies much of the heat. However, examples in Europe, such as in Sweden and Denmark, demonstrate the possibility of using lower carbon sources in district heating (two-thirds of energy supply is renewable in the Swedish district heating system and almost 60 per cent in Denmark) (IEA 2019a).

The biggest challenge for district heating is the large-scale infrastructure required and the need for wholesale systemic change, which explains the current low level of uptake. There have been various approaches to encouraging uptake of district heating. In many cases, institutions such as hospitals or government buildings have adopted district heating schemes. In other cases, large urban centres have shifted to district heating. For example, Denmark introduced a zoning system, whereby connection to the heat or natural gas network was mandatory in those areas while banning heat pumps, whereas heat pumps were subsidised outside these regions (Hanna et al. 2016).

Solar energy for heating and cooling

Since first deployed in 2005, solar thermal heat capacity has expanded to 470 GWth (thermal) nearly as much as solar PV capacity, mostly driven by deployment in China (IEA 2018a), as well as regions with high water heating needs (relative to heating) and high solar irradiance. This increase has also been driven by the implementation of sustainable cooling policies to limit cooling demand. However, as of 2018, solar thermal still only meets just over 2 per cent of space and water heat demand, which means that the sector would need a 10 per cent per year increase by 2030 to meet 8 per cent of building sector heat demand (IEA 2018a and 2019a). To date, the fastest growing technology is solar PV with storage (through chilled water/ice), with increasing sales in the Mediterranean, Middle East and Australia. Innovations in this space include flexible solar AC units (which adjust their capacity to the solar electricity available), as well as liquid desiccant evaporative cooling. Innovations in solar cooling include liquid desiccant cooling, which relies on cooling liquids. This simultaneously dehumidifies and cools the air, and is particularly useful in humid and hot areas (IEA 2018b and 2019b).

More efficient gas appliances

Most straightforward would be switching to condensing gas boilers, which are 95-100 per cent efficient and provide a more efficient alternative to conventional boilers. In dense areas, district heating and cooling systems can substitute for gas-based equipment, although this involves considerable investment in infrastructure. If substitution is not possible, switching all remaining conventional gas boilers to gas hybrid heat pumps and condensing boilers would be required to curb natural gas demand and reduce CO_2 emissions from heating. Policies imposing minimum efficiency requirements on gas appliances, like the Canadian 100 per cent efficiency space heating regulation by 2030, will be required to phase out low-efficiency gas systems. These minimum efficiency requirements need to ramp up to 150 per cent by 2050 for all heating appliances (IEA 2019a). Options to repurpose the gas grid to 'greener gas' such as hydrogen and biomethane are explored at the local level, but more R&D and demonstration projects are required to support the deployment of these solutions, beyond the local level.

Hydrogen

Hydrogen is a versatile and potentially carbon-free fuel, which can be used in diverse applications including transport and heating. The first barrier to the roll-out of hydrogen though is the difficulty of producing low-carbon hydrogen at competitive costs with natural gas. When produced from fossil fuels (via steam methane reformation – SMR, coal gasification or partial oil oxidation), which currently makes up 96 per cent of the world's hydrogen production (CCC 2018b), the carbon intensity of hydrogen – in this case also known as 'grey hydrogen' – can range from 205-600 gCO_2/kWh depending on the assumptions (Sustainable Gas Institute 2017).[1] One option to reduce the carbon intensity of hydrogen is to combine steam methane reforming with CO_2 capture and storage (CCS), the so-called blue hydrogen, which can result in carbon intensity as low as 20 gCO_2/kWh (Sustainable Gas Institute 2017). When produced from water electrolysis using carbon-free electricity, the hydrogen produced is zero carbon, also known as green hydrogen. If combined with decentralised renewable generation (for example wind or solar farms), this pathway also has the potential to use curtailed electricity from renewables, by storing it in the form of gas ('Power-to-gas'). Costs of hydrogen by electrolysis are widely seen as higher than via SMR (Mulder et al. 2019, IEA 2019e) although there are claims that at least in certain niches, green hydrogen may start to become competitive over the coming decade (Glenk and Reichelstein 2019).

Another major barrier to the hydrogen economy is the infrastructure required to store, transport and deliver hydrogen to consumers. In countries with an extensive natural gas network, a key opportunity around the hydrogen economy is the possibility to re-use the natural gas distribution networks, thereby avoiding the cost of decommissioning under strong decarbonisation policies. Current regulation in Europe only allows a share of 5 per cent (volumetric) of hydrogen in the natural gas distribution networks, due to concerns over pipe permeability, embrittlement and operation of existing gas end-use appliances. While full decarbonisation would require the replacement of 100 per cent of natural gas by hydrogen, current trials such as the GHRYD project in Northern France which started in 2017 are exploring the injection of greater volumes (up to 20 per cent) of hydrogen in the gas grid (ENGIE 2019). The UK's £25 million Hy4Heat project, planned for 2020, will explore the feasibility of natural gas grid conversion to hydrogen in the UK.

Another pathway under investigation is domestic fuel cells for onsite electricity generation. The leading market for this option is Japan with its ENE-Farm hydrogen fuel cell installations surpassing 300 000 units in 2019 (Klippenstein 2019). By contrast, in Europe, the ene.field project has demonstrated domestic electricity generation with hydrogen fuel cells micro-CHP (combined heat and power) at a much smaller scale, having installed 1000 units across ten countries since 2012 (European Commission 2019a).

Solid biomass and biomethane

A final set of renewable options for space heating is bioenergy in the form of domestic solid biomass boilers or biomethane injection into the natural gas grid. Currently, 30 per cent of domestic heat is still supplied by traditional biomass. Traditional biomass used in stoves and heaters is often sourced unsustainably, burned inefficiently and has been linked with numerous health problems (Goldemberg and Coelho 2004). In comparison, modern biomass such as wood pellets in stoves only constitutes 5 per cent of current heat provision in homes (IEA 2018a). Domestic boilers need a relatively high grade biomass pellets to operate efficiently (CCC 2018a). While modern biomass is theoretically a carbon-neutral renewable resource, whether the large-scale logistics of producing, upgrading and transporting biomass pellets around the world is indeed sustainable remains controversial. Land use change and potential deforestation, biodiversity loss, soil depletion or water use are additional concerns likely to constrain the amount of biomass which can be sustainably sourced (Creutzig et al. 2015).

Other bioenergy applications such as converting agricultural residues and municipal solid wastes to biomethane that can be injected into the gas grid, allow for the scope for bio-feedstock to be broadened and make use of what would otherwise be waste products, while continuing to use existing infrastructure. In France, for example, 44 biomethane injection stations injected 406 GWh of biomethane into the gas grid in 2017, which suggests rapid progress since the first pilot station in 2011 (Gaz Réseau Distribution France 2017).

4. Challenges and Opportunities of Electrification of Heat in Buildings

Electrification of residential and commercial heating can pose significant challenges to the design and operation of the electricity system. Sources of flexibility, both on the consumer and infrastructure side, will be key to alleviating these potential impacts.

4.1 Impact on Electricity Demand

A first set of challenges involves the impact of heat electrification on the electricity demand curve, which directly affects the power system's operation, as well as generation and transmission capacity requirements.

Winter and summer peaks

There has been increased attention to the relationship between temperature and electricity demand (Thornton et al. 2016; Cassarino et al. 2018). The sensitivity of the electricity system towards variation in heat demand is called thermo-sensitivity. The thermo-sensitivity of an electricity system is measured by the rate at which electricity demand increases per degree Celsius of temperature decrease. For example, in France, where electricity provides 18 per cent of residential heat demand (European Commission 2019b), the thermo-sensitivity of the system reaches 2400 MW/^{o}C (or 0.04 kW/^{o}C/capita) when temperatures fall below 1^{o}C, which is significantly higher than in the UK (800 MW/^{o}C or 0.01 kW/^{o}C/capita) where only 8 per cent of residential heating is electrified (RTE 2018). This suggests that electrification of heat would increase the power system's exposure to fluctuations in heat demand.

Additionally, in cold climates, the electricity profile is very different from the heat demand profile. Figure 9 shows the 2015 hourly profile of residential heat and total electricity demand in the UK (Charitopoulos et al. 2019).[2] While demand for electricity remains relatively constant throughout the year, heat demand is highly seasonal, with a fourfold variation between average summer and winter demand. Linking electricity to heat could therefore completely reshape the electricity demand profile, adding seasonality. Finally, the scale of peak demand and the rate at which the heat sector reaches these peaks is much greater than in a traditional power system. Reducing peak demand is particularly important, as it is typically met by 'peaking' fossil-based generation units (usually gas plants), and constitutes one of the largest challenges and sources of uncertainties to the electrification of heating (Chaudry et al. 2015; Eyre and Baruah 2015; Watson et al. 2019).

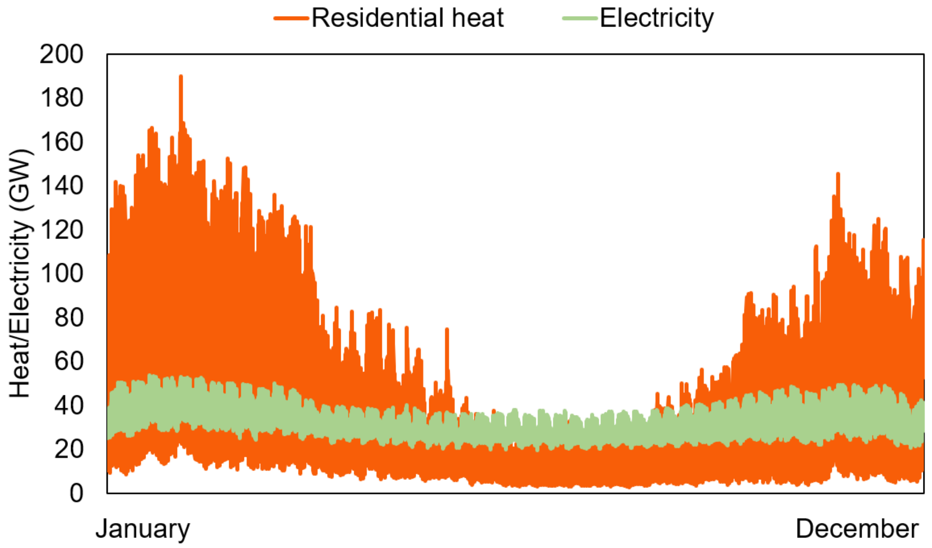

Figure 9 Total electricity and residential heat demand profiles in 2015 in the UK.

Source: authors based on Charitopoulos et al. (2019).

Increased electrification of heating, combined with lower heat pump efficiency on colder days, could drastically impact peak demand in winter. In the IEA Fast Transition scenario to 2050, heat pumps make up 30 per cent of the global heating equipment capacity by 2050, but this value increases to 45 per cent in the EU (IEA 2019a). A 50 per cent share of heating capacity by heat pumps would increase peak load by 60 per cent in the UK (Cooper et al. 2016). In 2050, a peak day in January could require 68 GW for heating, that is12 per cent of daily peak, or 69 GW in the morning , that is18 per cent of morning peak (Renaldi et al. 2017).

Rapid increase in energy services including cooling demand is also putting increasing strain on power systems. In 2017, cooling accounted for 15 per cent of peak electricity demand on average, and up to 50 per cent in some cities in China and India in summer (IEA 2018b).

In the IEA Fast Transition scenario, higher cooling and electrified heating demand is likely to increase peak demand. In China, where 1.1 billion AC units are expected to be owned by Chinese households by 2050, the evening peak could be one and a half times higher than the daily load (IEA 2019a).

Sources of flexibility

Hot water storage provides an opportunity to reduce the impact of electrification of heating demand, as well as secure heating supply at colder hours. For example, in the UK, combining heat pumps with hot water storage could help shift 15 per cent of the peak heating load to off-peak hours (Renaldi et al. 2017).

For gas-connected homes, another option to secure the heat supply under cold conditions is by pairing a heat pump with continued use of natural gas, through the use of hybrid heat pumps (Zhang et al. 2018).

Finally, another way to add flexibility to the system is to couple larger heat pumps with district heating or cooling networks. District level heat pumps typically have a higher coefficient of performance (EHPA 2017), and can enable more flexible operations, using the thermal inertia and flexibility provided by the heat networks (Schweiger et al. 2017).

Connected appliances and smart metering

To avoid electrification of heat having a large impact on both average and peak electricity demand, smart appliances combined with heat storage could: 1) reduce overall energy consumption through better management of overall household energy demand, and 2) shift peak demand by producing heat off peak. In particular, smart meters can help regulate load as a function of weather patterns. The pairing with storage capacity to shift the cooling load to off-peak hours, possibly when solar PV generation is available, is an example. These demand-side management options need to be facilitated with new tariff structures, such as (dynamic) off-peak electricity pricing, with the support of smart meters using time-of-use tariffs (Eid et al. 2016, Karlsen et al. 2020). For example, in the US, a 55 per cent decrease in cooling demand during peak hours was achieved following the implementation of a ‘rush hour reward’ scheme (BPIE 2016).

In the case of heating, the potential for load shifting and peak reduction is highly dependent on the system’s energy efficiency and the thermal storage available (Arteconi and Polonara 2018). Schemes to shift electric heating load are being explored in the context of all-electric houses in Norway (Karlsen et al. 2020). However, flexible operation of heating systems will be enormously challenging on a cold winter day, particularly without the use of flexible heating systems such as hybrid heat pumps.

Another critical element in any effort to manage demand is the growing deployment of smart meters, which has driven down costs. Roughly 800 million smart meters were installed as of 2017, 500 million in China alone, resulting in a 75 per cent drop in smart meter costs relative to 2010 (IEA 2019a). Furthermore, digitalisation and access to this data could also boost innovation and research to better tailor solutions to consumers.

4.2 Outlook for Future Demand

Demand for cooling and other energy services has increased dramatically since 2000. From 2020 to 2050, population is expected to grow by about 30 per cent, and up to 50 per cent in the Middle East, one of the regions of highest demand for cooling (World Bank 2019). The urbanisation rate is likely to reach 66 per cent and the number of cooling degree days is expected to grow by 25 per cent on average by 2050, with up to 37 per cent growth in regions like Mexico (IEA 2018b).

Despite continued improvements in efficiency, electrification of space heating and an increase in cooling needs could lead to an increase in power demand by 25 per cent, especially in developing economies with high cooling needs. Global electricity demand for space cooling alone could increase by up to 35 per cent (IEA 2019a). In the next decade, ten AC units could be sold every second, so addressing AC performance is of paramount importance (IEA 2018b).

Aside from changing how heat is supplied, demand-side response solutions are key to lowering heat demand in buildings and enabling greater heat electrification without imposing a strain on electricity systems.

Building envelope performance

One of the key levers of demand-side response is improving building envelope performance (Reyna and Chester 2017).

Improvements to building envelope need to be tailored to climate zones and those identified as the main levers for improving building efficiency in each zone are:

- Hot climates: building orientation, wall-to-window ratios, green roofs, reflective contours and connected blinds/shutters;
- Cold climates: ventilation with heat recovery, thermographic measurements and advanced insulation (multiple-pane windows, foam spray, reduction of thermal bridges);
- Mixed climates: improved thermal inertia, smarter ventilation and low emissivity windows.

In all climates, these improvements need to be accompanied by better energy management through sensors, consumption and storage based on energy prices or incentives.

Building codes play an important role. Gillingham et al. (2018) describe the debates over the effect of residential building codes. For example, Jacobsen and Kotchen (2013) find that when Florida tightened its code, electricity and natural gas consumption both fell (by 4 per cent and 6 per cent respectively) and that effects were more pronounced on the hottest and coldest days. By contrast, for California, Levinson (2016) finds that houses built after the state's strict residential code was established consumed 10–15 per cent less electricity and 25 per cent less gas than those built before the codes although the reductions were similar to those seen in states with much less stringent codes.

In any case, currently codes only cover just over half of total floor area (IEA 2019b), which equates to 38 per cent of energy use and half of CO_2 emissions. Moreover, two-thirds of new buildings are put up in countries which have not implemented clear guidelines. While building codes extended to 54 countries by 2017, including China, India and Turkey, the stringency of these policies is not increasing as fast as floor area and energy demand (IEA 2019a). In the IEA clean energy transition outlook, renovation rates of existing building stock need to double by 2050 (IEA 2019a). As global floor area is expected to increase by 80 per cent, building efficiency policies need to be carefully designed and implemented to ensure maximum coverage of new buildings to avoid lock-in effects. Furthermore, in poorly ventilated dwellings, there is a concern that some building efficiency improvement measures, such as increased insulation, can lead to reduced indoor air quality (Derbez et al. 2018). Building efficiency measures will therefore have to be implemented in a way which does not lead to unintended consequences for occupant health. The design of combined air ventilation and cleaner systems, such as Clean-Air Heat Pumps (Sheng et al. 2017), suggest that there is a rising interest in tackling indoor air quality and heating efficiency in a combined way.

At the global level, investments are needed to support innovation required to deliver on this rapid transition to a low carbon heating system and policies will be needed to support such investments. In the IEA projection which is consistent with a 2°C target (and which still does not assume full decarbonisation of the heat sector), energy investments in buildings increase from US $4.9 trillion in 2017 to US $5.4 trillion by 2050, and are mainly directed to improving building envelopes. The early timing of these investments is particularly important, to avoid 1) lock-in effects, for example, the possibility of having new inefficient buildings with lifetimes as long as 50 years, and 2) increased renovation and energy costs from delaying improvements, for example, a ten-year delay could incur $2.5 trillion in extra spending (IEA 2019a).

Increasing AC efficiency

Appliance efficiency improvements are also needed to balance the increasing electricity demand for cooling and other services. The average seasonal energy efficiency ratio (SEER), which measures the energy performance of AC units, has steadily improved from 2.4-2.7 in 1990, to 3.8-4.2 in 2018.[3] However, the potential of AC unit efficiency improvement remains largely untapped., as average values remain much lower than appliances available on the market. On average, most AC units sold have a SEER of 2 to 8 below that of the best available units on the market. In the United States, the best available SEER on the market is more than three times that of the average SEER. In China, one of the fastest growing markets, the average SEER is 4.4, though units with a SEER reaching 8.3 are available at comparable prices. Using currently available high performance AC units could therefore already curb cooling energy demand by half.

Setting minimum energy performance (MEP) for appliances is another lever for policy makers. MEPs are by far the most used policy tool, covering 40 per cent of cooling, heating and appliances energy demand. However, the best covered appliances (for example, lighting), do not coincide with the greatest source of emissions (for example, space heating) (IEA 2019a), which suggests the potential for improvements.

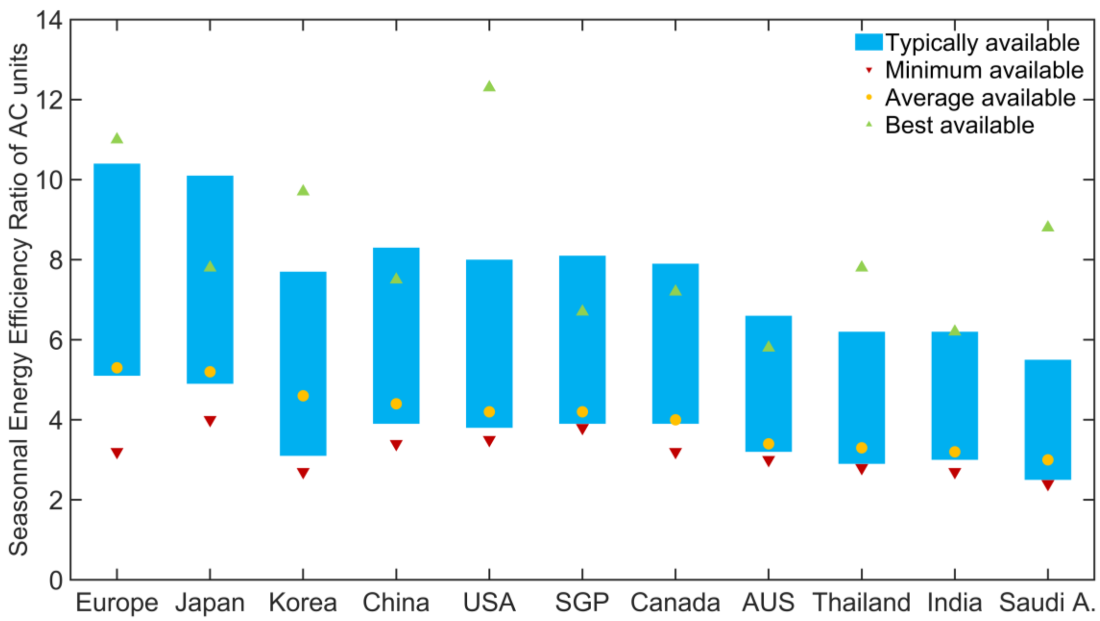

Figure 10 SEER of minimum, average, best and the range of typically available AC units in different regions (SGP = Singapore, Saudi A. = Saudi Arabia, AUS = Australia).

Source: authors based on IEA (2019b).

Globally, 1.5 billion households have access to cooling and demand is expected to grow substantially as rising incomes and temperatures drive ownership of AC and, importantly, utilisation. Even under the most optimistic scenarios, the ambition is simply to limit projected increases in electricity consumption via significant improvements in appliance efficiency and building envelopes. MEP policies are required to encourage the adoption of high efficiency ACs which are already available on the market and phase out the lower efficiency range. Further improvements to existing designs (for example, using solid or liquid desiccants to reduce latent heat of water vaporisation) will be required to reach the twofold efficiency increase target. In developed economies, efficiency improvements actually outweigh the increase in electricity demand, resulting in a slight decrease in electricity consumption.

4.3 Impact on Infrastructure and Total Energy System Cost

Electrification of heating comes at a cost, both to the householder – from an investment and operating cost perspective – and to the overall system. Systems integration costs typically arise from generation and transmission capacity deployment to meet the higher electricity demand and potential infrastructure decommissioning cost.

Total system cost

From a whole system perspective, the cost of transitioning from the incumbent heating system to a lower carbon one also includes infrastructure, capacity and decommissioning costs. For example, when comparing the total system costs of electrification, hydrogen and hybrid pathways to decarbonise heating in the UK, Strbac et al. (2018) found that annual costs were in a range of $109 billion and $123 billion/yr,[4] assuming a 2050 emissions targets in the heating sector of 10 or 30 $MtCO_2$/yr, where the hybrid pathway was lowest cost and hydrogen the highest. If a zero emission target was pursued by 2050, the hybrid and electrification pathways only increase costs by a further 5 per cent whereas the cost of the hydrogen pathway increases by some 35 per cent, past $162 billion/yr, owing to the higher cost of producing zero-carbon hydrogen from electrolysis. By contrast, in a separate UK study, the electrification pathway was found to be twice as expensive as the hydrogen pathway, which suggests the high dependence of these findings on infrastructure cost (for example, CCS, gas grid conversion and grid reinforcement cost) and technology performance (for example, CO_2 capture efficiency of CCS plants) (Element Energy and E4Tech 2018). Other factors such as hourly heat demand and technology cost assumptions are also highly influential in these assessments. More systems level studies are required to quantify the overall cost to the energy system of electrifying domestic and commercial heating.

Impact on the natural gas infrastructure

Globally, 30 per cent of domestic heat is supplied by natural gas, and up to 85 per cent in natural gas dominated heating systems such as the UK (BEIS 2018). Under high electrification scenarios, the gas network could become underutilised, leading to these networks becoming stranded assets, thereby incurring significant decommissioning cost. At the UK scale, electrification of residential heat demand causes an 18 per cent reduction in annual gas supply in the distribution network, due to a shift from natural gas boilers to heat pumps (Qadrdan et al. 2019).

In the IEA Fast Transition Scenario, regions with extensive natural gas networks (for example North America, Western Europe and Eurasia), do not decommission their existing gas networks, and natural gas still supplies 15 per cent of space and water heating demand in 2050 (IEA 2019a). This scenario, however, does not consider full decarbonisation of the heat sector. One major concern has been that an increase in the decarbonisation targets for the heat sector could lead to a drop in natural gas demand, thereby forcing natural gas grid operators into decommissioning the gas grid (Frontier Economics 2016). Substituting natural gas with greener gas (for example, hydrogen or biomethane) at the distribution level, is one option to avoid costs associated with decommissioning the gas grid, while complying with heat decarbonisation targets (Sustainable Gas Institute 2017).

CO_2 removal to allow for less stringent decarbonisation targets

National levels studies of full heat decarbonisation showed that the total system cost of a decarbonisation pathway could increase dramatically with the stringency of the decarbonisation target by 2050 (Element Energy and E4Tech 2018, Strbac et al. 2018). It is still unclear whether 1) more stringent targets will drive electrification further, and reduce or even phase out reliance on natural gas networks, or 2) emissions from the building and industrial sectors which are expensive to mitigate will be offset with the deployment of CO_2 removal methods. Future whole systems studies of electrification of heating need to explore the optimal level of decarbonisation and the role of these CO_2 removal methods.

The value of lost load

Total system cost is also highly related to the security criteria adopted for the electricity grid. The optimal level of security which is required to supply the electricity peak demand is very dependent on household’s Value of Lost Load, or VOLL, which measures the cost of disrupting power supply for consumers and is often incorporated into standards established by the regulator (see Box 2). While the security of electricity supply is of paramount importance for commercial and industrial consumers to sustain their economic activity, the extent to which higher consumer flexibility, encouraged by an increased knowledge of consumption provided by smart-metering devices, could lower the VoLL is a further opportunity to explore in the context of reducing the impact of electrification of heat on electricity systems.

Box 2: Value of lost load in the residential sector

Since the economy is highly dependent on electricity, disruptions in power supply can impose significant costs. Conversely, designing an electricity system with a high level of security typically involves adding power generation capacity and lowering the overall capacity factor of the system, which is equally costly to the economy. The point at which the marginal damages (from an interruption in electricity supply) equals the marginal cost of maintaining the security of the supply is the optimal level of security of the system, and provides a measure of the Value of Lost Load (VoLL) (Röpke 2013, Schröder and Kuckshinrichs 2015, CEPA 2018).

VoLL can vary widely dependent on the sector, the type of service provided by electricity and the level of consumption. Given its role in regulatory efforts, it is crucial to quantify VoLL across different sectors of the economy in different regions (London Economics 2013, CEPA 2018). While VoLL for industrial and commercial activities can be calculated using added value metrics as proxies (London Economics 2013), quantifying VoLL in the residential sector is not as straightforward.

First, VoLL is closely linked to consumer Willingness-To-Pay (WTP) for a reliable electricity supply or Willingness-to-Accept (WTA) a power outage, which is often expressed as a monetary value over a period of time (e.g., 1 hour or 8 hours). Consumer preference is therefore central to determining VoLL.

An additional challenge is related to the conflicting driving forces between consumption and VoLL. On the one hand, the electrification of residential heating, by increasing reliance on electricity at the household level, could put additional pressure on VoLL, by resulting in a higher WTP/WTA. For example, a survey in the UK showed that VoLL was higher in the UK for all-electric households as compared to gas households (London Economics 2013). On the other hand, an increase in consumption theoretically lowers VoLL, which is sometimes expressed as monetary value per unit of consumption (CEPA 2018).

The extent to which electrification of heating will impact VoLL in the residential sector therefore remains very uncertain.

4.4 The Power Sector Is Decarbonising, But Not Fast Enough

As observed in Figure 4, 70 per cent of emissions from buildings come from indirect emissions associated with electricity generation (IEA 2019a). The electricity sector is going through a rapid decarbonisation in many countries. For example, since 2010, the carbon intensity of electricity in the UK has dropped from 450 to 280 gCO_2/kWh (European Commission 2019b). In many other economies, including leading emerging markets, however, the carbon intensity of electricity is not decreasing as fast as demand for electricity is increasing. Between 2010 and 2017, the average carbon intensity of electricity decreased from 1000 gCO_2/kWh to 750 gCO_2/kWh in China, and from 1200 gCO_2/kWh to 1000 gCO_2/kWh in India, but sectoral emissions continue to increase (IEA 2018b). Efforts to fully decarbonise the electricity grid will be pivotal in delivering a low carbon heating system through electrification.

On the other hand, buildings floor area is expected to almost double (+96 per cent) between today and 2050 reaching 460 billion m^2 by mid-century. Even assuming optimistic energy intensity improvements, this increase will likely drive up building energy demand. Out of the 230 billion m^2 of new floor area, 85 per cent will be built in emerging economies, most of which have yet to decarbonise their power sector. Over the next decade alone, 77 billion m^2 of new floor area will be built, primarily in countries like Brazil, India or Indonesia, where potential high demand for cooling will be critical (IEA 2019a).

4.5 Consumer Preferences and Technology Adoption

Because heating sources are highly dispersed, decarbonisation of heat will largely rely on households' willingness to switch away from fossil-based heating systems to new, more efficient and renewable heating systems (Michelsen and Madlener 2012). This could mean connecting to a district heating and cooling network or installing a heat pump. While adopting more energy-efficient technologies could provide energy savings, research suggests that households do not necessarily act rationally when it comes to technology adoption, and that other factors such as thermal comfort play an important role in the final choice to adopt a new technology. Depending on tenancy type (owner/tenant), environment (urban/rural) or income level, households might have different technology adoption rates. Constraints on technology adoption can also involve space considerations (for a ground source heat pump for example) or building density (connection to a district heating network will be unlikely in a rural environment) (Cayla et al. 2011, Michelsen and Madlener 2012, Li et al. 2018). Accounting for this heterogeneity in household structure and preferences will likely be crucial when designing policies to encourage the uptake of low carbon and efficient heating and cooling technologies. In particular, there are potential issues associated with how consumers process information, actual behaviour versus engineering models including rebound effect, split responsibility between bill payers, residents, and those making the investments, and changes in thermal comfort.

There have been relatively few empirical or experimental studies of consumer purchasing or switching behaviour regarding heating and cooling equipment. One area where there has been attention is on the role of information. Ramos et al. (2015) review many of the informational barriers and proposed policy solutions associated with residential energy efficiency, of which a number of specific studies address heating and cooling. Allcott and Sweeney (2016) found that providing information on efficiency of conventional hot water heaters did not in itself increase the purchase of more energy-efficient units, but a combination of large rebates plus information did increase the market share of more efficient heaters. Moreover, salespeople only targeted energy efficiency information at consumers who expressed interest in the subject, but did not discuss it with the disinterested majority. Bollinger and Hartmann (2019) found information alone could reduce demand over the long term, but to change short-term elasticity, automation technology would also be needed.

There have been a number of studies that question many of the more optimistic predictions of techno-economic modelling, which echoes the literature seeking to describe the energy efficiency 'gap' (Gerarden et al. 2017). In consumer surveys, respondents typically overestimate the energy costs associated with low-usage goods (for example, computers or mobile phones) and underestimate the energy costs of high-usage goods (for example, water heaters) (Attari et al. 2010). Relatedly, real-world implementation may not match claimed savings. For example, ex ante engineering estimates overstated actual conservation by 13 per cent in an experiment providing households with insulation and HVAC appliances (Dubin et al. 1986). Even more glaring, a programme to replace inefficient air conditioners in Mexico actually led to increased electricity consumption, in stark contrast to engineering predictions of significant energy savings (Davis et al. 2014). Another challenge is that the outcomes of home energy retrofits are difficult for homeowners to observe – Giraudet et al. (2018) identify a moral hazard whereby contractors take advantage of the relative lack of knowledge regarding the quality of energy efficiency measures being implemented leading to lower energy savings, particularly for work conducted on Fridays.

Other important considerations include ascertaining whether interventions can be demonstrated as effective, whether they can lead to any appreciable effect or even lead to a rebound effect. Alberini et al. (2016) found that those who replaced their heat pumps but who did not receive any incentive to do so reduced their electricity usage by 16 per cent, whereas those who did receive an incentive actually did not reduce their electricity usage. Furthermore, the larger the rebate a household received, the less the household reduced energy usage. Davis et al. (2014) also employ matching to evaluate a program in Mexico that subsidised replacement of refrigerators and air-conditioning units and find that although refrigerator replacements reduced electricity consumption by 8 per cent on average annually, air-conditioner replacements actually increased electricity consumption, again consistent with a rebound effect. Rivers and Shiell (2016) examine Canadian subsidies for natural gas furnace retrofits and find strong evidence for free riding – they estimate that in the long run, more than 80 per cent of subsidy recipients would have eventually purchased identical furnaces without a subsidy.

Another major challenge is the tension between ownership, tenancy and bill payers. Gillingham et al. (2012) find tenants who pay for their own household energy are 16 per cent more likely to change their temperature setting at night. Furthermore, owner-occupied homes are 13 -20 per cent more likely to have additional insulation. Myers (2019) finds that landlords responsible for energy bills are more likely to convert from less efficient oil heat to more efficient natural gas heat, compared with landlords who do not pay for energy despite the availability of significant cost savings.

One might also expect that environmental attitudes might be correlated with choice of heating or cooling technology and that 'greener' consumers might be most likely to be early adopters of low-carbon heating or cooling systems. Curtis et al. (2018) find that environmental attitudes have no impact on fuel or technology choice and the main determinant of home heating fuel and technology choice is simply proximity to the gas grid. Similarly, although Lange et al. (2014) find a negative correlation between heating expenditures and environmental behaviours, they did not identify any relationship between environmental attitudes or perceptions and heating expenditures.

Finally, thermal comfort can also be a key deterrent to switch to heat pumps as a heating system. The use of heat pumps requires a good level of insulation to operate, as space heating will be typically slower than with a conventional gas-powered central heating system. In households connected to the gas grid, hybrid heat pumps which can be operated with both electricity and natural gas represent a good opportunity to secure heat supply during colder spells (Zhang et al.2018).

The use of heat pumps could however increase thermal comfort during the warm seasons, as they can also be used for cooling. One of the key drivers of heat pump sales is interest in reversible heat pumps, which can be used for both heating and cooling driven by demand for space cooling. In the US, mini-split ductless heat pumps are on the rise (Weorpel 2018) owing to a higher SEER and low operating temperature for heating. Of course, improved thermal comfort also means greater energy use in summers In temperate climate zones, where there had previously been little air conditioning, energy would be increasingly devoted to cooling that would otherwise not have taken place with the existing infrastructure.

Aside from incentives to adopt new heating technologies, one other important consideration is the willingness of jurisdictions to impose outright bans on further use of gas for heating. For example, the UK has mandated new homes should not have a gas connection by 2025 (Harrabin 2019) and in late 2020, the city of San Francisco banned natural gas in all new residential construction from mid-2021 (Dineen 2020). The Netherlands has mandated that all homes will move away from natural gas by 2050, but a large number of municipalities including Rotterdam, Amsterdam and Utrecht have agreed on near-term measures to increase the number of 'gas-less neighbourhoods' in the coming years by disconnecting public housing, not permitting gas in new buildings and encouraging district heating and other options such as electric or hybrid heat pumps (van den Ende 2017).

4.6 Demand Elasticity to Energy Prices and Energy Poverty

Another key impact of, and potential limitation to, electrification (and decarbonisation) of heating is the incurred cost to the household.

Fuel poverty is generally defined as the inability to heat own's home at a correct standard, owing to a combination of factors including household income, energy efficiency of the dwelling and energy prices (Charlier and Kahouli 2018). It is a major issue across the world, including in advanced economies. In the United Kingdom, 3000 people died in 2018 because of fuel poverty (Chapman 2018). In Canada, one million households are affected by energy poverty, during both winter cold and summer heat waves (Tardy and Lee 2019).

Switching to a more efficient heating system typically requires an upfront investment, which could have implications for household energy spending. Micro-CHP fuel cells typically represent the highest investment from the householder's perspective. Capital costs range from $17 000-23 000 per unit in Japan, to $37 000 per unit in Europe (Dodds et al. 2015). Heat pumps also represent a substantial investment, with capital and installation costs ranging between $6700 and $15 300 for an air-source heat pump, and $12 000 to $26 700 for an ground-source heat pump (BEIS 2018, carbon Connect 2019, Renewable Energy Hub 2019). Modern biomass boilers can cost between $9300 and $20 000, depending on the degree of sophistication (carbon Connect 2019, Renewable Energy Hub 2019). Hydrogen boilers are expected to cost the same as a conventional gas boilers, anywhere between $700 and $4000 per unit depending on the size, but installation and pipeline conversion work could cost as much as $1300 to 5500 (CCC 2018b, Strbac et al. 2018, carbon Connect 2019). All of the proposed alternatives are therefore likely to represent a significant upfront cost for residential or commercial consumers when compared to current natural gas boilers (capital costs between $700 and 3300 depending on the size for condensing boilers) or conventional electric systems (electric storage heaters typically cost $300-600 per panel) (carbon Connect 2019).

Owing to a higher energy efficiency, operating costs of alternative heating systems are expected to be lower than for fossil fuel boilers or conventional electric heaters (Honoré 2018). However, annual costs and potential savings are largely dependent on energy costs – natural gas, electricity, biomass, hydrogen and on the incumbent system. In many countries which rely on natural gas for heating, the average price of natural gas is typically lower than the price of electricity (European Commission 2019b). Concerning the conversion to a ‘greener gas’, the cost of hydrogen fuel is currently prohibitive. Estimates of the cost of hydrogen from electrolysis can vary from over 24 $/MWh (Sustainable Gas Institute 2017) to as low as 10 $/MWh with best available technology (Mathis and Thornhill 2019), which is still twice the cost of natural gas. Hydrogen from steam methane reformation with CCS can cost as low as 7 $/MWh, but only assuming a pre-existing CCS infrastructure (Sustainable Gas Institute 2017).

Energy savings generated when retrofitting a heating system to a more efficient one are also very variable. In a comparative assessment of residential heating technologies for a semi-detached house in Quebec, ASHPs are found to generate savings relative to a conventional electric heater when electricity prices reach 44$/MWh, while GHSPs need a electricity price of 95 $/MWh to break even (Pedinotti-Castelle et al. 2019). The scale and variation in the electricity price profile in time can also impact the competiveness of heating technologies. When considering variable electricity price profiles, heat pumps are only competitive with gas boilers and electric heaters for a large household and a short run electricity price regime (average price of 27 $/MWh), but heat pumps and micro-CHPs are never competitive at higher electricity prices (average price of 96 $/MWh), regardless of the household size (Vijay and Hawkes 2017). Rebates and tariffs can be instrumental to the adoption of these technologies. The eligibility of heat pumps for the Renewable Heat Incentive (RHI) in the UK (UK Government 2014) or for local incentives in China (Zhao et al. 2017) are examples of such policies.

Finally, the introduction of more stringent decarbonisation policies to decarbonise the electricity grid could also lead to an increase in electricity prices.

Many studies have attempted to quantify the short-term and long-term price elasticity of energy demand (see Labandeira et al. 2017 for a meta-analysis). There have been a number of studies of residential demand (for example, Risch and Salmon 2017, Charlier and Kahouli 2018), to better inform the design of energy policies. Price elasticities of heating demand in particular are generally found to be influenced by income level, household type and total household expenditures (Schulte and Heindl 2017). A study on the elasticity of heating demand in Germany showed that the energy demand of lower-income consumers was much less elastic than that of higher-income consumers (Schulte and Heindl 2017). This highlights household energy as a necessary good and suggests that higher energy prices resulting from policies incentivising demand reduction could disproportionally impact lower income households (He and Reiner 2016). National and local policies such as the state-mandated heating prices in Quebec, via the control over hydro power generation (Tardy and Lee 2019), or the Energy Voucher in France allocated to the poorest 15 per cent of households (Charlier and Kahouli 2018), are required to ensure that electrification of heating (or decarbonisation more generally) does not decrease the overall welfare of vulnerable heating consumers.

5. Outlook for the Electrification of Heat

The role of electrification in future decarbonisation pathways has been examined in the context of meeting both global 1.5 and 2°C targets by the end of the century (IEA 2019a, Knobloch et al. 2019) and regional economy-wide 80 per cent-100 per cent emissions reduction targets by mid-century (Connolly et al. 2014; Element Energy and E4Tech 2018; Honoré 2018; Strbac et al. 2018; National Grid 2019a; White and Rhodes 2019).

5.1 Global Outlook

In the IEA Faster Transition pathway to 2050, which is consistent with a 2°C target, the building sector undergoes the most rapid economy-wide decarbonisation, as direct and indirect CO_2 emissions drop from 9.5 $GtCO_2$ in 2017 to 1.2 $GtCO_2$ in 2050 (IEA 2019a). Energy demand for services which are already electrified *(*for example, cooling) grows substantially in emerging economies, as level of development, increasing income and rising temperatures drive ownership of AC and other appliances. Deep efficiency improvements to appliances and building envelopes are required just to limit the global increase in electricity consumption to 30 per cent. This is achieved through a 50 per cent increase in AC unit performance by 2030, and a twofold increase by 2050. In developed economies, efficiency improvements actually outstrip the projected increase in electricity demand, resulting in a slight decrease in electricity consumption. Residential heating demand is primarily met with bioenergy and solar thermal, which reaches three billion households by 2030 and represents 85 per cent of the installed heating capacity by 2050. Heat pumps go through a rapid scale up, growing from 3 per cent of installed capacity to 30 per cent by 2050. To dampen the impacts that this growth might have on the electricity grid, the efficiency of heat pumps also needs to increase, to reach a COP of 3.5 in cold climates, 5 in temperate climates, and 8-9 in climates where reversible HPs are used for both heating and cooling. Even in this ambitious scenario, natural gas still plays a role in the heating system, supplying 15 per cent of space and water heating demand by 2050 (IEA 2019a).

5.2 Regional Outlooks

At the regional level, decarbonisation pathways are highly dependent on technology performance and cost assumptions, as well as on existing heat supply and regulations to either discourage heat or actively promote alternatives. At the EU level, a decarbonisation study assessing the impact of an economy-wide 80 per cent reduction targets suggests the high potential of heating networks fuelled by heat pumps to decarbonise EU heating demand (Connolly et al. 2014). In the Northeast US, a scenario consistent with a 40 per cent emissions reduction target by 2030 projects electrification to meet 23 per cent of total heating demand (through air and ground source heat pumps), thereby increasing the electricity peak demand by 15 per cent and the heavy reliance on natural gas through the shift of oil boilers towards gas boilers (National Grid 2019a). The study does not, however, provide a clear pathway to meet the 80 per cent reduction target by 2050, nor does it discuss the feasibility of replacing natural gas by a low carbon alternative. In the UK, two studies have recently compared electrification, hydrogen and hybrid pathways under different decarbonisation targets (Element Energy and E4Tech 2018, Strbac et al. 2018), with significantly different results (see Section **Error! Reference source not found.**), which suggests the high dependence of these findings on infrastructure cost (for example, CCS, gas grid conversion and grid reinforcement cost) and technology performance (for example, CO_2 capture efficiency of CCS plants). Other factors such as hourly heat demand and technology cost assumptions are also highly influential in these assessments.

5.3 The Impact of More Stringent Emissions Reduction Targets

As net zero targets by 2050 are being legislated around the world, future pathways are expected to cover scenarios consistent with a 100 per cent economy-wide decarbonisation target by mid-century. Most previous decarbonisation outlooks to 2050 had explored the implications of a 80-85 per cent emissions reduction target (Connolly et al. 2014, Element Energy and E4Tech 2018, Honoré 2018, IEA 2019a). Full decarbonisation of the heating sector would involve drastic changes in the structure and operation of the energy system.

National-level studies of full heat decarbonisation showed that the total system cost of a decarbonisation pathway could increase dramatically with the stringency of the decarbonisation target by 2050 (see Section **Error! Reference source not found.**) (Element Energy and E4Tech 2018, Strbac et al. 2018) although the CCC (2019) report on net zero for the UK Government notes that the total cost of meeting the 80 per cent target as assessed in 2008 was identical to the total cost of meeting 100 per cent reduction (1-2 per cent of GDP). Absent further analysis, it is unclear whether 1) more stringent targets will drive electrification further, shifting away from a reliance on natural gas networks, with implications for the security of the electricity supply, or 2) emissions from the building and industrial sectors which are expensive to mitigate will be offset with the deployment of CO_2 removal methods (for example the UK relying on bioenergy with carbon capture and storage to offset remaining emissions, see CCC (2019)) or via international offsets. Future whole systems studies of the electrification of heating will need to explore the optimal level of decarbonisation and the role of these CO_2 removal methods.

6. Conclusions

This br explored the present role and future opportunities and challenges for electrification of heating in buildings.

Electricity is expected to play an ever-larger role in emerging countries, owing to a booming demand for cooling and other energy services. High efficiency heat pumps are projected to reach much higher level of deployment, complemented by biomass boilers, solar thermal, and a switch to high-efficiency gas boilers and/or hybrid heat pumps.

Despite scattered incentives for market-ready renewable and more efficient heating systems, the heating sector remains heavily fossil-fuel dominated. Key barriers to electrification of heating include 1) the impact of annual and peak electricity demand, 2) the simultaneous increasing demand for electricity services such as cooling, and 3) the potential financial and social impacts of increased cost of heating.

Policies such as building codes, appliance efficiency labels and incentives for the adoption of low carbon or more efficient heating and cooling systems are key to enabling decarbonisation of heating and cooling through electrification, but empirical evidence to date is still quite weak although existing evidence points to the severe challenges of rapid adoption of new technologies in the buildings sector.

The three innovation and policy levers of electrification of heating and cooling in the buildings sector are 1) setting minimum efficiency requirements for cooling and heating equipment, 2) exploiting synergies between heating/cooling equipment and storage, smart metering and district networks to enhance flexibility and reduce impact on peak demand, 3) implementing policy measures to improve building envelopes. Table 2 summarises the key innovation, investment and policy challenges and opportunities in decarbonising heating and cooling in the building sector.

Finally, most previous heating decarbonisation outlooks to 2050 do not achieve net zero emissions although this may begin to change as more large economies such as the UK and France have begun to adopt legally binding net zero targets. Full decarbonisation of the heating sector involves drastic changes in the structure and operation of the energy system. The role of CO_2 removal methods to offset residual emissions from heating needs to be explored to determine the optimal level of electrification (and decarbonisation) for residential heating system, in order to maintain reliability and affordability of heating.

Table 2 Opportunities in electrifying heating in buildings and associated challenges

Issue	Possible opportunities	Associated challenges
Increasing demand for electricity driven by cooling demand	Building performance improvement	Actual performance does not meet technical expectations
	Coincidence of solar PV peak and high cooling demand	Potential mismatch between rate of PV and AC uptake
	Improving appliance efficiency (via standards)	Uneven evidence over savings associated with building codes
	Voluntary schemes (for example, label technology performance; use same metric to facilitate like-for-like comparison)	Questions over how to overcome informational barriers and consumer interest in energy savings
Impact on existing infrastructure (for example, gas network) and total system cost	Improving efficiency of gas appliances	Technology lock-in to continued use of natural gas
	Hybrid heat pumps that avoid need for radical shift and stranded costs and deliver better performance	Incomplete shift away from natural gas resulting in significant residual emissions
	CO_2 removal (CDR) to offset residual emissions	Concerns over possible mitigation deterrent effect
	Revise VoLL to reflect changing views of security of supply and need for capacity expansion	VoLL is built into regulations and utility investment decisions so may be slow to change
	Repurpose gas grid with greener gas (hydrogen, biomethane or carbon-neutral synthetic fuels)	Potential competition between electrification and greener gas routes
Increased electricity peak demand	Encourage synergies with other alternative technologies (distributed solar PV, district heating, thermal storage)	Difficulty of coordinating timing of deployment different build-out rates
	Enhance flexibility with thermal storage	Minimal evidence on willingness of consumers to respond
	Shift peak demand to off-peak hours with smart meters and dynamic electricity pricing	Slow uptake of time of use pricing even in jurisdictions that have deployed smart meters
Technology adoption	Household level incentives for the purchase and operation of renewable heating technologies	Success strongly dependent on how consumers process information, split responsibility over bills and investments
	Market based measures/economy of scale to reduce the cost of new	Questions over actual behaviour versus engineering models, rebound effect,

	systems	effectiveness of incentives
	Reversible heat pumps for thermal comfort in winter and summer	Greater energy use in summers and energy devoted to cooling that would otherwise not have taken place

References

Alberini, A., W. Gans and C. Towe (2016), ‘Free riding, upsizing, and energy efficiency incentives in Maryland homes’, *The Energy Journal*, **37** (1), 259–290.

Allcott, H. and R. L. Sweeney (2016), ‘The Role of Sales Agents in Information Disclosure: Evidence from a Field Experiment’, *Management Science*, **63** (1), 21–39.

Arteconi, A. and F. Polonara (2018), ‘Assessing the demand side management potential and the energy flexibility of heat pumps in buildings’, *Energies*, **11** (7), 1–19.

Attari, S. Z., M. L. DeKay, C. I. Davidson and W. Bruine de Bruin (2010), ‘Public Perceptions of Energy Consumption and Savings’, *Proceedings of the National Academy of Sciences*, **107** (37), 16054–16059.

BEIS (2018), *Clean Growth - Transforming Heating, Overview of Current Evidence*, UK Department of Business Energy and Industrial Strategy, accessed at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/766109/decarbonising-heating.pdf.

Beyond Zero Emissions (2018), *Zero Carbon Industry Plan: Electrifying Industry*, accessed at http://bze.org.au/electrifying-industry-2018/.

Bollinger, B. K. and W. R. Hartmann (2019) ‘Information vs. Automation and Implications for Dynamic Pricing’, *Management Science*, **66** (1), 290–314.

BPIE (2016), *Smart Buildings in a Decarbonised Energy System 10 Principles To Deliver Real Benefits for Europe’s Citizens*, Buildings Performance Institute Europe, accessed at http://bpie.eu/wp-content/uploads/2016/11/BPIE-10-principles-final.pdf.

BERC (2018), *China building energy use 2018*, Building Energy Research Center, accessed at https://berc.bestchina.org/Files/CBEU2018.pdf.

CEPA (2018), *Study on the estimation of the Value of Lost Load of electricity supply in Europe,* Cambridge Economic Policy Associates, accessed at https://www.acer.europa.eu/en/Electricity/Infrastructure_and_network development/Infrastructure/Documents/CEPA study on the Value of Lost Load in the electricity supply.pdf.

carbon Connect (2019), *Supporting material 1: comparison of different types of low carbon heating from a householder perspective*, accessed at https://www.policyconnect.org.uk/cc/sites/site_cc/files/supporting_material_1_tables_of_different_low_carbon_heating_options_0.pdf.

Cassarino, T. G., E. Sharp and M. Barrett (2018), ‘The impact of social and weather drivers on the historical electricity demand in Europe’, *Applied Energy*, **229**, 176-185.

Cayla, J. M., N. Maizi and C. Marchand (2011), ‘The role of income in energy consumption behaviour: Evidence from French households data’, *Energy Policy*, **39** (12), 7874–7883.

Chapman, P. (2018), ‘Fuel poverty crisis: 3,000 Britons dying each year because they can’t heat their homes, study shows’, *The Independent*, 22 February 2018, accessed at https://www.independent.co.uk/news/business/news/cold-weather-uk-winter-deaths-europe-polar-vortex-a8224276.html.

Charitopoulos, V., C. K. Chyong and D. Reiner (2019), ‘Modelling & optimisation of decarbonisation pathways for UK heat sector’, EPRG & CEEPR International Energy Policy Conference, “The Good Fight Against GHG Emissions”, London, 2-3 September 2019, accessed at https://www.eprg.group.cam.ac.uk/wp-content/uploads/2019/09/V.-Charitopoulos_2019.pdf

Charlier, D. and S. Kahouli (2018), ‘From residential energy demand to fuel poverty: Income-induced Non-linearities in the Reactions of Households to Energy Price Fluctuations’, *FAERE Working Paper*, No. 11.

Chaudry, M., M. Abeysekera, S. H. R. Hosseini, N. Jenkins, and J. Wu (2015), ‘Uncertainties in decarbonising heat in the UK’, *Energy Policy*, **87**, 623–640.

CCC (2018a), *Biomass in a low-carbon economy*, Committee on Climate Change, November 2018, accessed at https://www.theccc.org.uk/wp-content/uploads/2018/11/Biomass-in-a-low-carbon-economy-CCC-2018.pdf.

CCC (2018b), *Hydrogen in a low-carbon economy*, Committee on Climate Change, November 2018, accessed at https://www.theccc.org.uk/wp-content/uploads/2018/11/Hydrogen-in-a-low-carbon-economy.pdf .

CCC (2019), *Net Zero: The UK’ s contribution to stopping global warming*, Committee on Climate Change, May 2019, accessed at https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/.

Connolly, D., H. Lund, B. V. Mathiesen, S. Werner, B. Möller, U. Persson, T. Boermans, D. Trier, P. A. Østergaard and S. Nielsen (2014), ‘Heat roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system’, *Energy Policy*, **65**, 475–489.

Cooper, S. J. G., G. P. Hammond, M. C. McManus and D. Pudjianto (2016), ‘Detailed simulation of electrical demands due to nationwide adoption of heat pumps, taking account of renewable generation and mitigation’, *IET Renewable Power Generation*, **10** (3), 380–387.

Creutzig, F., N. H. Ravindranath, G. Berndes, S. Bolwig, R. Bright, F. Cherubini, H. Chum, E. Corbera, M. Delucchi, A. Faaij, J. Fargione, H. Haberl, G. Heath, O. Lucon, R. Plevin, A. Popp, C. Robledo-Abad, S, Rose, P. Smith, A. Stromman, S. Suh, S. and O. Masera (2015), ‘Bioenergy and climate change mitigation: An assessment’, *GCB Bioenergy*, **7** (5), 916–944.

Curtis J., D. McCoy and C. Aravena (2018), ‘Heating system upgrades: The role of knowledge, socio-demographics, building attributes and energy infrastructure’, *Energy Policy*, **120**, 183-196.

Davis, L. W., A. Fuchs and P. Gertler (2014), ‘Cash for Coolers: Evaluating a Large-Scale Appliance Replacement Program in Mexico’, *American Economic Journal: Economic Policy*, **6** (4), 207–38.

Derbez, M., G. Wyart, E. Le Ponner, O. Ramalho, J. Ribéron and C. Mandin (2018), ‘Indoor air quality in energy-efficient dwellings: Levels and sources of pollutants’, *Indoor Air*, **28** (2), 318–338.

Dineen, J.K. (2020), No more natural gas in new San Francisco buildings starting next year, *San Francisco Chronicle*, 12 November

Dodds, P. E., I. Staffell, A. D. Hawkes, F. Li, P. Grünewald, W. McDowall, and P. Ekins (2015), ‘Hydrogen and fuel cell technologies for heating: A review’, *International Journal of Hydrogen Energy*, **40** (5), 2065–2083.

Dubin, J. A., A. K. Miedema and R. V. Chandran (1986), ‘Price Effects of Energy-Efficient Technologies: A Study of Residential Demand for Heating and Cooling’, *RAND Journal of Economics*, **17** (3), 310–25.

EHPA (2017), *Large scale heat pumps in Europe*, European Heat Pump Association., accessed at https://www.ehpa.org/fileadmin/red/03._Media/03.02_Studies_and_reports/Large_heat_pumps_in_Europe_MDN_II_final4_small.pdf.

EHPA (2019), *Market Data Stats Tool*, European Heat Pump Association, accessed at https://www.ehpa.org/market-data/.

Eid, C., E. Koliou, M. Valles, J. Reneses and R. Hakvoort (2016), ‘Time-based pricing and electricity demand response: Existing barriers and next steps’, *Utilities Policy*, **40** (June), 15–25.

Element Energy and E4Tech (2018), *Cost analysis of future heat infrastructure options Report for National Infrastructure Commission March 2018*, accessed at https://www.nic.org.uk/wp-content/uploads/Element-Energy-and-E4techCost-analysis-of-future-heat-infrastructure-Final.pdf.

Enerdata (2019), *The Future of Air Conditioning*, 26 September 2019, accessed at https://www.enerdata.net/publications/executive-briefing/the-future-air-conditioning-global-demand.html

EIA (2019), *Annual Energy Outlook 2019*, Energy Information Administration, accessed at https://www.eia.gov/outlooks/aeo/data/browser/#/?id=2-AEO2019&sourcekey=0.

ENGIE (2019), *The GHRYD demonstration project*, accessed athttps://www.engie.com/en/businesses/gas/hydrogen/power-to-gas/the-grhyd-demonstration-project/.

European Commission (2019a), *Ene.field*, accessed at http://enefield.eu/.

European Commission (2019b), *EUROSTAT*, accessed at https://ec.europa.eu/eurostat/data/database%0A.

Eyre, N. and P. Baruah (2015), ‘Uncertainties in future energy demand in UK residential heating’, *Energy Policy*, **87** (December), 641–653.

Friedmann, S. J., Z. Fan and K. Tang (2019), *Low-Carbon Heat Solutions for Heavy Industry : Sources , Options , and Costs Today*, Center for Global Energy Policy, Columbia University, 7 October 2019, accessed at https://energypolicy.columbia.edu/research/report/low-carbon-heat-solutions-heavy-industry-sources-options-and-costs-today.

Frontier Economics (2016), *Future Regulation of the UK gas grid: Impacts and institutional implications of UK gas grid future scenarios – a report for the CCC*, accessed at https://www.theccc.org.uk/wp-content/uploads/2016/10/Future-Regulationof-the-Gas-Grid.pdf.

Gaz Réseau Distribution France (2017), *Renewable Gas French Panorama 2017*, accessed at http://www.grtgaz.com/fileadmin/plaquettes/en/2018/Overview-Renewable-Gas-2017.pdf.

Gerarden, T. D., R. G. Newell and R. N. Stavins (2017), 'Assessing the Energy Efficiency Gap', *Journal of Economic Literature*, **55** (4),1486–1525.

Gi, K., F. Sano, A. Hayashi, T. Tomoda, and K. Akimoto (2018), 'A global analysis of residential heating and cooling service demand and cost-effective energy consumption under different climate change scenarios up to 2050', *Mitigation and Adaptation Strategies for Global Change*, **23** (1), 51–79.

Gillingham, K., M. Harding and D. Rapson (2012), 'Split Incentives in Residential Energy Consumption', *The Energy Journal*, **33** (2), 37–62.

Gillingham, K., A. Keyes and K. Palmer (2018), 'Advances in Evaluating Energy Efficiency Policies and Programs', *Annual Review of Resource Economics*, **10** (1), 511-532.

Giraudet, L. G., S. Houde and J. Maher (2018), 'Moral hazard and the energy efficiency gap: Theory and evidence', *Journal of the Association of Environmental and Resource Economists*, **5** (4), 755-790.

Glenk, G., and S. Reichelstein (2019), 'Economics of converting renewable power to hydrogen', *Nature Energy*, **4**, 216–222

Goldemberg, J. and S. T. Coelho (2004), 'Renewable energy—traditional biomass vs. modern biomass', *Energy Policy*, **32** (6), 711-714.

Hanna, R., B. Parrish and R. Gross (2016), *Best practice in heat decarbonisation policy: A review of the international experience of policies to promote the uptake of low-carbon heat supply*, UKERC Technology and Policy Assessment.

Harrabin, R. (2019), 'Gas Heating Ban for New Homes from 2025', *BBC News*, 13 March, accessed at https://www.bbc.co.uk/news/science-environment-47559920.

He, X., and D. M. Reiner (2016), 'Electricity demand and basic needs: Empirical evidence from China's households', *Energy Policy*, **90**, 212-221.

Heinen, S., P. Mancarella, C. O'Dwyer and M. O'Malley (2018), 'Heat electrification: The latest research in Europe', *IEEE Power and Energy Magazine*, **16** (4),69–78.

Honoré, A. (2018), *Decarbonisation of heat in Europe : implications for natural gas demand*, Oxford Institute for Energy Studies, accessed at https://ora.ox.ac.uk/objects/uuid:c808f872-16de-4d88-8190-5c17abcae0bd.

IEA (2018a), *Renewables 2018: Analysis and Forecasts to 2023*, International Energy Agency, Paris, accessed at: https://webstore.iea.org/market-report-series-renewables-2018.

IEA (2018b), *The Future of Cooling: opportunities for efficient air conditionning*, International Energy Agency, Paris, accessed at https://www.iea.org/reports/the-future-of-cooling.

IEA (2019a), *Perspectives for the Clean Energy Transition: The Critical Role of Buildings*, International Energy Agency, Paris, accessed at https://webstore.iea.org/perspectives-for-the-clean-energy-transition.

IEA (2019b), *Tracking Clean Enegy Progress*, International Energy Agency, Paris, accessed at https://www.iea.org/tcep/.

IEA (2019c), *World energy balances - Overview*, International Energy Agency, Paris, accessed at https://webstore.iea.org/world-energy-balances-2019.

IEA (2019d), *World Energy Investment 2019*, International Energy Agency, Paris, accessed at https://webstore.iea.org/world-energy-investment-2019.

IEA (2019e), *The Future of Hydrogen: Seizing Today's Opportunitie*s, International Energy Agency, Paris, accessed at https://webstore.iea.org/download/direct/2803

IEA Statistics (2019), *IEA Statistics*, International Energy Agency, Paris, accessed at https://www.iea.org/statistics/.

Jacobsen, G. D. and M. J. Kotchen (2013), 'Are building codes effective at saving energy? Evidence from residential billing data in Florida', *Review of Economics and Statistics*, **95**, 34–49.

Karlsen, S. S., M. Hamdy and S. Attia (2020), 'Methodology to assess business models of dynamic pricing tariffs in all-electric houses', *Energy and Buildings*, **207**, 109586.

Klippenstein, M. (2019), 'FCW Exclusive: Tokyo Fuel Cell Expo 2019 - 300,00 Ene-Farms', *FuelCellsWork.com*, 18 April 2019, accessed at https://fuelcellsworks.com/news/fcw-exclusive-tokyo-fuel-cell-expo-2019-300000-ene-farms/.

Knobloch, F., H. Pollitt, U. Chewpreecha, V., Daioglou and J. F. Mercure (2019), 'Simulating the deep decarbonisation of residential heating for limiting global warming to 1.5°C', *Energy Efficiency*, **12** (2), 521–550.

Labandeira, X., J. M. Labeaga and X. López-Otero (2017), 'A meta-analysis on the price elasticity of energy demand', *Energy Policy*, **102**, 549–568.

Lange, I., M. Moro and L. Traynor (2014), 'Green hypocrisy?: Environmental attitudes and residential space heating expenditure', *Ecological Economics*, **107**, 76–83.

Lechtenböhmer, S., L. J. Nilsson, M. Åhman and C. Schneider (2016), 'Decarbonising the energy intensive basic materials industry through electrification – Implications for future EU electricity demand’, *Energy*, **115**, 1623–1631.

Levinson, A. (2016) ‘How Much Energy Do Building Energy Codes Save? Evidence from California Houses’, *American Economic Review*, **106** (10), 2867–2894.

Li, P. H., I. Keppo and N. Strachan, N. (2018), ‘Incorporating homeowners’ preferences of heating technologies in the UK TIMES model’, *Energy*, **148**, 716–727.

London Economics (2013), *The Value of Lost Load (VoLL) for Electricity in Great Britain: Final report for OFGEM and DECC*, OFGEM and DECC, July 2013, accessed at https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/224028/value_lost_load_electricty_gb.pdf.

Luh, S., S. Budinis, S. Giarola, T. J. Schmidt and A. Hawkes (2019), ‘Long-term Development of the Industrial Sector – Case Study about Electrification, Fuel Switching, and CCS in the USA’, *Computers & Chemical Engineering*, **133**, 106602.

Lund, H., *S.* Werner, R. Wiltshire, S. Svendsen, J. E. Thorsen, F. Hvelplund and B. V. Mathiesen (2014) ‘4th Generation District Heating (4GDH): Integrating smart thermal grids into future sustainable energy systems’, *Energy*, **68**, 1–11.

Mathis, W. and J. Thornhill, J. (2019), ‘Hydrogen’s Plunging Price Boosts Role as Climate Solution’, *Bloomberg Climate Changed*, 21 August 2019, accessed at https://www.bloomberg.com/news/articles/2019-08-21/cost-of-hydrogen-from-renewables-to-plummet-next-decade-bnef.

Michelsen, C. C. and R. Madlener (2012), ‘Homeowners’ preferences for adopting innovative residential heating systems: A discrete choice analysis for Germany’, *Energy Economics*, **34** (5), 1271–1283.

Mohajerani, A., J. Bakaric and T. Jeffrey-Bailey (2017), ‘The urban heat island effect, its causes, and mitigation, with reference to the thermal properties of asphalt concrete’, *Journal of Environmental Management*, **197**, 522–538.

Mulder, M., P. Perey and J. L. Moraga (2019), *Outlook for a Dutch hydrogen market: economic conditions and scenarios*, University of Groningen Policy Paper No 5, accessed at https://www.rug.nl/ceer/blog/ceer_policypaper_5_web.pdf

Myers, E. (2019), ‘Are Home Buyers Inattentive? Evidence from Capitalization of Energy Costs’, *American Economic Journal: Economic Policy*, 2019, **11** (2), 165-188.

National Grid (2019a), *Northeast 80x50 Pathway*, accessed at https://www.nationalgridus.com/News/Assets/80x50-White-Paper-FINAL.pdf.

National Grid (2019b), *The non-gas map*, accessed at https://www.nongasmap.org.uk/.

Natural Resources Canada (2019), *The National Energy Use Database (NEUD)*, accessed at http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/data_e/publications.cfm?attr=0#b.

Nekrasov, A. S., S. A. Voronina, and V. V. Semikashev (2012), ‘Problems of residential heat supply in Russia’, *Studies on Russian Economic Development*, **23** (2), 128–134.

Paige, J., C. McMillan, D. Stenberg, M. Muratori, L. Vimmerstedt and T. Mai (2017), *Electrification Futures Study : End-Use Electric Technology Cost and Performance Projections through 2050*, accessed at www.nrel.gov/publications.%0Ahttps://www.nrel.gov/docs/fy18osti/70485.pdf.

Pedinotti-Castelle, M., M. F. Astudillo, P.-O. Pineau and B. Amor (2019), ‘Is the environmental opportunity of retrofitting the residential sector worth the life cycle cost? A consequential assessment of a typical house in Quebec’, *Renewable and Sustainable Energy Reviews*, **101**, 428–439.

Qadrdan, M. R. Fazeli, N. Jenkins, G. Strbac and R. Sansom (2019), ‘Gas and electricity supply implications of decarbonising heat sector in GB’, *Energy*, **169**, 50–60.

Ramos, A., A. Gago, X. Labandeira and P. Linares (2015), ‘The role of information for energy efficiency in the residential sector'', *Energy Economics*, **52** (S1), S17-S29.

Renaldi, R., A. Kiprakis and D. Friedrich (2017), ‘An optimisation framework for thermal energy storage integration in a residential heat pump heating system’, *Applied Energy*, **186**, 520–529.

Renewable Energy Hub (2019), *A guide to heat pump prices in 2019*, accessed at https://www.renewableenergyhub.co.uk/main/heat-pumps-information/a-guide-to-heat-pump-prices-in-2019/.

RTE (2018), *Bilan Electrique 2018*, Réseau de Transport d’Electricité, accessed at https://www.rte-france.com/sites/default/files/be_pdf_2018v3.pdf.

Reyna, J. L. and M. V. Chester (2017), ‘Energy efficiency to reduce residential electricity and natural gas use under climate change’, *Nature Communications*, **8** (2017), 1–12.

Risch, A. and C. Salmon (2017), ‘What matters in residential energy consumption: Evidence from France’, *International Journal of Global Energy Issues*, **40** (1/2),101–137.

Rivers N. and M. L. Shiell (2016), ‘Free Riding on Energy Efficiency Subsidies: The Case of Natural Gas Furnaces in Canada’, *The Energy Journal*, **37**(4), 239–266.

Röpke, L. (2013), ‘The development of renewable energies and supply security: A trade-off analysis’, *Energy Policy*, **61**, 1011–1021.

Schröder, T. and W. Kuckshinrichs (2015), ‘Value of lost load: An efficient economic indicator for power supply security? A literature review’, *Frontiers in Energy Research*, **3**, 1–12.

Schulte, I. and P. Heindl (2017), ‘Price and income elasticities of residential energy demand in Germany’, *Energy Policy*, **102**, 512–528.

Schweiger, G., J. Rantzer, K. Ericsson and P. Lauenburg (2017), ‘The potential of power-to-heat in Swedish district heating systems’, *Energy*, **137**, 661–669.

Sheng, Y., L. Fang and J. Nie (2017), 'Experimental analysis of indoor air quality improvement achieved by using a Clean-Air Heat Pump (CAHP) air-cleaner in a ventilation system', *Building and Environment*, **122**, 343–353.

Shuxue, X., W. Yueyue, N. Jianhui and M. Guoyuan (2019), ''Coal-to-electricity' project is ongoing in north China', *Energy*, 116525.

Staffell, I., D. Brett, N. Brandon and A. Hawkes (2012), 'A review of domestic heat pumps', *Energy and Environmental Science,* **5** (11), 9291–9306.

Strbac, G., D. Pudjianto, R. Sansom, P. Djapic, H. Ameli, N. Shah, N. Brandon and A. Hawkes (2018), *Analysis of Alternative UK Heat Decarbonisation Pathways*, Imperial College London, accessed at https://www.theccc.org.uk/wp-content/uploads/2018/06/Imperial-College-2018-Analysis-of-Alternative-UK-Heat-Decarbonisation-Pathways.pdf.

Sustainable Gas Institute (2017), *A greener gas grid: What are the options? A White Paper*, July 2017, accessed at https://www.sustainablegasinstitute.org/a-greener-gas-grid/.

Tardy, F. and B. Lee (2019), 'Building related energy poverty in developed countries – Past, present, and future from a Canadian perspective', *Energy and Buildings*, **194**, 46–61.

Thornton, H. E., B. J. Hoskins and A. A. Scaife (2016), 'The role of temperature in the variability and extremes of electricity and gas demand in Great Britain', *Environmental Research Letters*, **11** (11), 114015.

UK Government (2014), *The Renewable Heat Incentive (RHI) scheme*, accessed at https://www.gov.uk/government/publications/2010-to-2015-government-policy-low-carbon-technologies/2010-to-2015-government-policy-low-carbon-technologies#appendix-6-renewable-heat-incentive-rhi.

van den Ende, E. (2017), *A revolution: The Netherlands kisses gas goodbye – but will it help the climate?*, Energy Post, 7 June 2017, accessed at https://energypost.eu/a-revolution-the-netherlands-kisses-gas-goodbye-but-will-it-help-the-climate/.

Vijay, A. and A. Hawkes (2017), 'The Techno-Economics of Small-Scale Residential Heating in Low Carbon Futures', *Energies*, **10** (11). 1915.

Watson, S. D., K. J. Lomas and R. A. Buswell (2019), 'Decarbonising domestic heating: What is the peak GB demand?', *Energy Policy*, **126**, 533–544.

Weorpel, H. (2018), *Mini-Split Heat Pumps Are One of the Fastest Growing HVAC Sectors, ACHR News*, 28 May 2018, accessed at https://www.achrnews.com/articles/137150-mini-split-heat-pumps-are-one-of-the-fastest-growing-hvac-sectors.

Werner, S. (2017), 'International review of district heating and cooling', *Energy*, **137**, 617–631.

White, P. R. and J. D. Rhodes (2019), *Electrification of Heating in the Texas Residential Sector*, Report prepared for Pecan Street by Ideasmiths LLC, accessed at https://www.pecanstreet.org/electrictexas/.

World Bank (2019), *World Development Indicators*, accessed at https://datacatalog.worldbank.org/dataset/world-development-indicators.

Zhang, X., G. Strbac, F. Teng and P. Djapic (2018), 'Economic assessment of alternative heat decarbonisation strategies through coordinated operation with electricity system – UK case study', *Applied Energy*, **222**, 79–91.

Zhao, H., Y. Gao and Z. Song (2017), 'Strategic outlook of Heat pump development in China', in *12th IEA Heat Pump Conference 2017*, 1–5.

Endnotes

[1] Accounting for the life cycle emissions of coal and natural gas supply.

[2] Heat demand profile only includes dwellings connected to the gas grid, which represents 71 per cent of UK dwellings (National Grid 2019b).

[3] The SEER values collected from the IEA are calculated as the ratio of cooling energy output in kWh, to energy input in kWh. By contrast, SEER values in the US are typically three times higher as they are calculated as the ratio of cooling energy output in British thermal units (BTU), to energy input in kWh.

[4] All cost data are presented in 2018 US$. British pound (GBP) and Canadian dollar (CAD) figures were converted using conversion rates of US$1 = 0.75 GBP (2018 exchange rate) and US$1 = 1.379 CAD (2016 exchange rate). US GDP deflators were used to convert cost data to 2018$ (World Bank 2019).